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Automotive Lighting and Human Vision

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With 270 Figures and 22 Tables

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Preface

It is possible to buy excellent books on human vision as well as about automotive lighting. Unfortunately, these books have little or no common content. But in fact these fields do overlap. Providing optimal conditions for human vision is what automotive lighting is all about.

Our motivation for writing this book arises from interdisciplinary studies of human vision and lighting. Initially we intended the book to provide background information on human vision to engineers working in automotive lighting. At the same time we planned to introduce basic concepts of automotive lighting to experts in human vision. However because of the intricate connections between human vision and automotive lighting, it turns out that the book provides new insights to anyone interested in either or both subjects.

The subject matter is complex and spans a number of disciplines from psychology to mechatronics. Hence there are very few individuals who are experts in all fields. Looking at the nature of human vision, it is surprising to find out how much every one of us takes it for granted. Rarely are we aware of how we use vision predominantly to verify our internal model of our surroundings. Many accidents, particularly at night, stem from the fact that our internal model misrepresented a significant part of our surroundings. Taking knowledge on human vision into account in the design of future automotive lighting systems reduces the risk of accidents at night.

After several futile attempts to write this book in a "standard way", we decided to create it in an innovation cell. This is an intense work and study session, where authors meet and write simultaneously. Three of the four authors were doubtful whether it could all be written in just one week, but were later surprised how much can be achieved in such a short and concentrated period. In fact within the week much more was accomplished than in either the three preceding or following months.

We would like to thank all those who contributed to the book. We are particularly grateful to Sabine Raphael, Bianca Lehde, Marco Eggert, Janet Wördenweber and all the external authors of the Spotlights.

December 2006 *Burkard Wördenweber, Jörg Wallaschek, Donald Hoffman and Peter Boyce*

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Index of Spotlights

We have used spotlights to illustrate the validity of the points made in this book. Many of the spotlights have been contributed by authors with different areas of expertise in various industries or institutes. We are grateful to the authors and appreciate their cooperation and the diversity of views they represent. You will recognise spotlights in the text by their special formatting. A list of the external authors of spotlights is provided at the end of the index.

External Spotlights

Author	Affiliation	Spotlight
Heiner Bubb	TU München	The closed loop: Driver – Car
Heiner Bubb	TU München	Glance and the perceived present
Heiner Bubb	TU München	Glance behaviour during driving
Heiner Bubb	TU München	Optical and kinaesthetic feedback
Marek Olivik	Visteon	Automotive projector modules
Mitch Sayers	Visteon	The emergence of the LED headlamp
Martin Formanek	Visteon	CAE in exterior lighting
Florian Haake	Genthe	Nanotechnology anti-fog coatings in automotive lighting and sensor applications
Milan Cejnek, Martin Kocian	Visteon	Advanced front lighting – Concept overview
Jasmin von Göler, Jörg Moisel	DaimlerChrysler	Automotive night vision systems
Vladimir Kubena, Jan Martoch	Visteon	Light guides for automotive application
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Fritz Lorek	Freelance journalist	The bulb can make a difference
Viren Merchant	Visteon	LED control
Svatopluk Bajer	Visteon	Exterior lighting – Lenses and reflectors history

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Vladimir Dobrus	Visteon	Impact behaviour of automotive headlamp
Ingo Schneider	Visteon	Guidelines for visibility and mounting requirements (SAE)
Sabine Raphael	University of Paderborn / L-LAB	Luminance as criterion to evaluate disability and discomfort glare
Patrick Kuhl	BMW	Compensating for a heavy load, sharp braking or accelerating, by headlamp-levelling systems
Markus Klein	Visteon	Dynamic lighting
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Jürgen Locher	Hella / L-LAB	Humanocentric design of driver assistance systems

1 Introduction

The book takes you, the reader, through the story of automotive lighting. You will find out how vision works, what the industry does for lighting and what conflicts remain to be solved. The book concludes with an outlook for lighting to improve our vision when driving, particularly at night. There are many questions we have asked ourselves in order to provide answers. The following dialogue between a (fictional) lighting expert, symbolized by "•," and an engineer or educated layperson, interested in the makings of successful automotive lighting systems, symbolized by "□", introduces the questions that motivated us. The answers you will find in more detail in the main chapters of the book.

How Vision constructs reality – Man is not a nocturnal creature!

□ As a car driver I would like to know more about automotive lighting. I know many people who dislike driving at night. I am sure good engineering could improve the situation. But what does a chapter on visual perception have to do with it?

• How can a good lighting system be designed without understanding of the needs of the driver? Automotive lighting is a means to an end, not an end in itself. How can you design a lighting system unless you know how the driver's visual system works, what it is capable of, and how the brain constructs the world from visual input?

□ Wait a moment! That sounds too complicated and philosophical for me. "The brain constructs the world …" We open our eyes and see. There is a picture, a set of pixels, rather like a camera, and that is it, isn't it?

• I am afraid it is not quite that simple. Vision is much more than just the set of pixels. The eye and our visual system do not work like a camera.

□ If it is not camera, what is it?

• It is a complete recognition system. It is programmed by nature, culture and our experience to model the world around us.

□ Are you trying to tell me that we don't see pixels, but instead have a complete model of the external world in our heads?

• That is almost true. Except it is by no means a complete model. We usually construct "reality" in our head that is limited to what we personally find relevant.

□ What is relevant to you might not be relevant to me?

• What is relevant to any one of us is determined first by the capabilities of our visual system and later by the sensitivity filters in our value system.

□ But surely, we are all made out of the same matter, have the same pigments in the receptor cells of our eyes and the same hardwiring?

• The early image-processing taking place in the retina is indeed similar for everyone, but once the visual cortex is reached differences can emerge. Evolution has favoured a brain that is not just hard wired, but one that can be programmed extensively in our growing years. This means that only people who were exposed to the same array of stimuli during their early years can be expected to have similar perceptions.

□ Does that mean that my great-grandfather was adapted only to driving at the speed of the horse-drawn coach?

• Yes it does. Every generation learns afresh. Part of the environment will be the same as the previous generation. But if we consider the influence of computer games on the visual system of the next generation, we will be surprised to find that our children have better visual acuity and faster peripheral responses than we do.

Automotive Lighting State-of-the-Art – Luckily we already have lights on our cars

- □ The automobile was invented more than one hundred years ago, and automobile lighting has evolved for decades. Can you point out the most important milestones with respect to vision and lighting?

- • Yes I can. But I will not only tell you about the historical development, but also try to give you an idea of the history behind the history.

- □ What do you mean by “The history behind the history”?

- • The evolution of technologies has never been a straightforward process, even if there seems to be continuity. Technological developments are typically influenced by changing environments and by the evolution of related technologies. Often progress is chaotic in nature and a small detail decides success or failure.

- □ Can you give an example?

- • Let’s take signature lighting. Do you remember the years before the turn of the millennium and the accompanying ‘doom and gloom’ in the run up to the year 2000? Do you remember the worries that computers would not function with the new dates? Some people worried that the sun would not rise. One of the car manufacturers very prominently fixed light guides to the headlamps of the cars and sold them as ‘angel eyes’. The public went crazy about the feature.

- □ I understand that it is important to know about the details of automotive lighting systems, but I have never come across a comprehensive description of the state-of-the-art.

- • Let’s look at how a headlight is made. Let’s see what makes up a working signal light. We should also look at interior lighting.

- □ Headlights are important to the appearance of the vehicle. How much does the designer have to take into account the overall styling and design of the vehicle?

- Today all lights are an integral part of vehicles. They are part of the exterior design and make use of the vehicle electronic architecture. But what can be done is constrained by a wide range of standards and regulations

□ It sounds as if lighting has to serve a lot of different masters, from design, via safety all the way to politicians.

- You are right. It is very difficult to understand what is going on without knowing about the conflicts and constraints that underlie the evolution of any technical system. It is therefore, a good idea to think about what the competing considerations are in the design of automotive lighting. They are not fuel efficiency against low emission, as in engine design, or ride comfort versus road holding as in the case of suspensions. The most obvious conflict in automotive lighting design is between good visibility for the driver and minimum glare for oncoming drivers. There are numerous other conflicts, such as effectiveness v. regulation, appearance v. cost and ease of maintenance v. complexity.

Fundamental Problems with Automotive Lighting – Lighting systems today are a compromise

□ Why is it so difficult to design a good lighting system?

- Because many different situations have to be taken into account. For example, old people have different visual capabilities than young people, so ideally they should have appropriately adjusted lighting. Lighting also has to work in a variety of environmental and weather conditions.

□ You mean fog lights?

- Adverse weather is just one of many conditions where the driver would welcome more support than our current lighting systems provide.

□ I did not mean the difficulties caused by different weather conditions. Rather I wanted to express my surprise that no one seems to have a concise idea about what “good” lighting means in contrast to “bad” lighting. Are there no clear design guidelines and regulations for the engineer?

- There certainly are, but they are deficient in a number of ways. For example, they are all expressed in terms of the performance of the visual system during daytime; but at night when automotive lighting is used, the performance of the visual system changes. Then there is the question of good for whom or under what circumstances. For example the lighting necessary to detect a pedestrian wearing dark clothes is different from that if the pedestrian is wearing white clothes. What is “good” lighting depends on what needs to be seen. To add to the confusion, what is “good lighting” for one driver may be “bad” lighting for the driver coming the other way.

□ So there really is no simple performance measure for automotive lighting?

- You are probably right that there is no simple performance measure for vehicle lighting. It could be argued that a lighting system that meets current regulations is “good” lighting, but that means accepting the limitations of current regulations. The real problem is that the effectiveness of automotive lighting is determined by many factors, many of which are outside the control of the lighting designer. The solution to this is lighting that can adapt to the conditions—more intelligent lighting.

Automotive Lighting and Mechatronics – New technologies paired with a better understanding of the real needs lead to better systems

□ Technologies are developing in many areas, for example high speed data communication, plasma displays or crash simulations. Surely there must be a chance to improve lighting systems and to make them more intelligent and user friendly.

- Yes, you are right. We have barely scratched the surface when it comes to development of intelligent lighting systems. All the ingredients are there for intelligent lighting systems i.e. systems that have some notion of what is happening around them and can assist the driver, whilst avoiding conflict with other traffic.

□ Is this not complexity for the sake of itself? Why should we make things more complicated than we really need? Wouldn't it be far easier to use "invisible" light?

- Many important lessons were learned when polarised light, ultraviolet light and finally infra-red light were used. The big headaches for all these lighting systems were the avoidance of adverse affects for other road users, the "missing" of some targets, and the presentation of images to the driver.

□ How should an intelligent lighting system present images to the driver?

- The governing principle of any user interface in an intelligent lighting system is 'make it familiar'. The driver should be able to interact with the interface in his natural environment. The system should not challenge the driver excessively i.e. the rule is 'do not overwhelm the user with irrelevant information'. Finally the information should be presented in intuitively understandable chunks.

□ Does this mean I will soon be seeing cars with grumpy or smiley faces?

- You are not far off. We know that the visual system recognises contours long before it checks colour. Lighting can take advantage of this.

□ Does that mean we all need to study how human vision works?

- Yes. Let's start again at the beginning of the book…

2 How Vision Constructs Reality

2.1 Visual construction

Automotive lighting serves one primary customer: the human visual system. To better serve customers one must make the effort to understand them thoroughly, taking into account their needs, goals, and behaviour. With vision as the customer, we readily assume good understanding - because we have successfully used our own visual system for several decades. But many of our preconceptions about vision and how it functions are in fact misconceptions, misguided not merely in details but in fundamentals (Hoffman 1998). Designers of automotive lighting must be aware of these tempting misconceptions and discard them in favour of modern understanding of the needs, goals, and behaviour of human vision. In this chapter we describe the structure and capabilities of the visual system, together with some common misconceptions about it and what it does.

A common misconception is that human vision functions basically like a camera, producing un-interpreted images of the objective state of the external world. It is true that the eye functions in part rather like a camera. A lens focuses an image at the back of the eye on the approx. 120 million photoreceptors of the retina (Dowling 1987). In this respect the eye is like a 120 mega-pixel camera, although only about 8 million of the photoreceptors are effective in high illumination. But the activity of 120 million photoreceptors is not the end product of the visual system; it is merely the initial input. The visual system itself consists of about 50 billion neurons and tens of trillions of synapses - roughly half of the cortex of the human brain (Spillmann, Werner 1990, Kandel et al 2000). You will not find anything like this complexity inside a camera.

Clearly it does not take 50 billion neurons and trillions of synapses simply to report the objective properties of the image at the eye; 120 million photoreceptors are enough for that. So what are all these neurons and synapses for? The short answer is that they are for constructing the rich visual worlds of our experience, replete with objects, colours, motions, textures, lighting, and three-dimensional depth. We do not see reality unadorned; we see a reality constructed by our visual systems (Gregory 1966, 1970, Hoffman 1998, Marr 1982). The complexity of the neural structure of the visual system mirrors the complexity of the constructive processes by which we create our visual worlds. Research in the cognitive and neural sciences has uncovered many of these constructive processes and the principles that guide their operation (Hoffman 1998, Knill, Richards 1996, Palmer 1999). Understanding these processes and principles is essential to understanding human vision, and to designing lighting systems adapted to its mode of operation. We describe below a few of these processes and principles, and discuss their implications for automotive lighting.

2.1.1 Constructing shape and depth

The image at the eye is sampled non-uniformly, which implies that human vision must attend sequentially to different parts of the visual field. As it happens, the image at the eye is two-dimensional, which means that human vision must construct all the three-dimensional shapes and depths that it sees, since three-dimensional geometry is not and cannot be explicitly contained in a two-dimensional image. In this section we discuss briefly how human vision constructs three-dimensional shapes and depths.

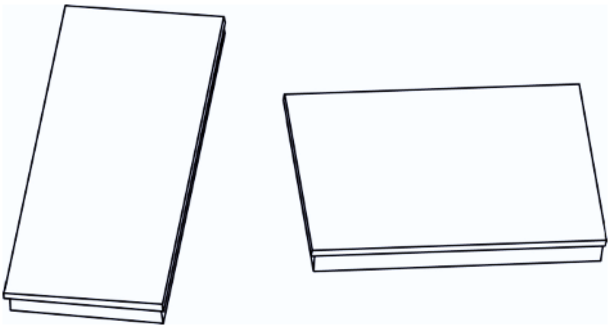


Fig. 2.1 Two boxes. The box on the left looks long and narrow; the box on the right looks short and fat. In fact they have the same dimensions. You can check this with a ruler.

We begin with examples to illustrate that human vision does, in fact, construct shapes and depths, since this claim might at first seem patently false. Consider the two boxes shown in Fig. 2.1 (Hoffman 1998, Shepard 1990):

Are they the same size or different? After a casual glance you might conclude that they are obviously quite different, with the box on the left looking long and narrow and the box on the right looking short and fat. But in fact they are exactly the same size, as you can verify for yourself with a ruler or tracing paper. How can our perceptions of such simple shapes be so dramatically incorrect? The answer is that human vision has rules by which it constructs three-dimensional shapes and depths. Simply by following these rules the visual system is led to construct strikingly different three-dimensional shapes for these two boxes. Of course the visual system is not following these rules explicitly, as though one were reading a recipe in a cookery book and following its instructions. Instead these rules are built into the computational architecture of the visual system and are engaged automatically when the visual system is presented with retinal images.

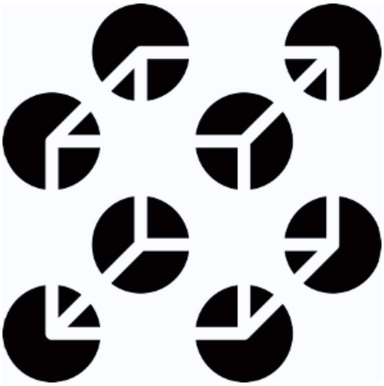


Fig. 2.2 The subjective Necker cube. The ghostly white lines you see floating between the black discs are entirely illusory. So also are the three-dimensional cubes you see. The visual system constructs all the three-dimensional shapes and objects that you see.

The two boxes clearly demonstrate that human vision constructs shape and depth, and that these constructions are fallible. This has implications for driving. The shape and depth of the road ahead, and of all the objects on or around the road, are all constructed in real time by the visual system of the driver and guide the driver's decisions and reactions. Understanding the rules by which these constructions are made and how these constructions are thereby fallible, designers of automotive lighting and warning systems can engineer these systems to anticipate the mistakes and misjudgements drivers are likely to make, and adjust accordingly the lighting and warnings.

Another illustration that human vision constructs depth and objects is a figure first devised by Bradley and Petry (1977), the subjective Necker cube (see Fig. 2.2).

Perhaps you see a ghostly cube floating in front of black discs. If you stare at the cube for a while, you might notice that it flips, so that a corner that was in front goes behind, and vice versa. The page at which you are now looking is of course flat, so that both of the three-dimensional cubes that you see must be fabricated by your visual system. The cubes are not literally there on the page until your visual system puts them there.

You can think of the visual system as functioning much like a scientist: collecting data and arriving at theories. The visual world that we experience now is simply the most recent theory concocted by our visual system. Alternatively you can think of the visual system as a detective, gathering visual clues and reaching an informed conclusion; you see the conclusions to which your visual system currently assigns the highest probabilities.

The key disanalogy between your visual system and scientists or detectives is that whereas the inferences of scientists or detectives are typically reached by a process that is conscious, the inferences of the visual system are typically reached by a process that is unconscious.

When you view the subjective Necker cube, the unconscious processing of your visual system arrives at two theories that it concludes, given the image data, have high probability. As a consequence you see both theories sequentially, flipping from one to the other.

Your visual system can construct more theories from the illustration of the subjective Necker cube. Think of the black discs in the illustration as holes in a white sheet of paper, and through the holes you see a cube behind the sheet of paper. Once you do this you will notice that your perception changes and you now see a new interpretation of the illustration - a cube appearing to float behind the holes instead of in front of black disks. As you attend to this new cube you will notice that it also flips, so that a corner in front goes behind and vice versa. This makes a total of four different cubes that your visual system has fabricated from a single illustration.

But you are fabricating more than just the three-dimensional shapes of these cubes. In the case where you see a cube floating in front of the black disks, you are also fabricating the straight lines that you see passing between the black discs. You can check for yourself that there are no lines between the discs, by simply covering the discs. The lines you see between the discs will suddenly disappear. If you uncover the black discs, the lines will appear again, despite your knowledge of their illusory status.

This shows that there can be multiple levels to the fabrications of the visual system. First it fabricates the straight lines in two dimensions. Then it assembles these lines into a three-dimensional cube. One fabrication built on the foundation of another fabrication. This is typical in the visual system, where the number of layers of fabrication is not limited to just two.

Spotlight

Structure from motion

We take it for granted that we see the world in three dimensions and in particular, that we see the depth of the world around us. Robust perception of depth is of course critical to successful driving. But it might be surprising to learn that since the image at the eye is only two-dimensional, any time we see depth we must construct that depth (Hoffman 2000). The processes by which we construct depth are laden with assumptions and are therefore fallible. In this example we discuss one of the processes by which we construct depth; we consider a key but fallible assumption on which it is based.

Human vision is adept at constructing three-dimensional shapes from the motions of points in two dimensions (Wallach, O’Connell 1953, Green 1961). An interactive example of this is available online in a Java applet here:

http://www.cogsci.uci.edu/%7Eddhoff/Sphere3.html

This applet allows you to explore how your perception of a rotating sphere changes as you change the number and colour of the moving dots, the axis and speed of the rotary motion, and the transparency or opacity of the shape. You can also get a feel for this in Fig. 2.3 which shows two frames from a film of a rotating cylinder. For the whole film, go to

http://www.cogsci.uci.edu/%7Eddhoff/vi6fig158.html

Each frame simply displays dots in two dimensions. But when human vision views the frames in a moving sequence, it proceeds to construct a three-dimensional cylinder. If you stereo-fuse the two frames in the Fig. 2.3 below, you can see this cylinder.

What is remarkable about this visual capacity is that human vision solves an ill-posed problem whenever it computes a three-dimensional shape and motion for an object from just the two-dimensional motions of its points. Recall that a mathematical problem is well posed if its solution exists, is unique, and varies continuously with the input data. Otherwise a mathematical problem is ill-posed. The problem human vision solves here is ill-posed because there are infinitely many three-dimensional interpretations that are theoretically compatible with the two-dimensional motions of the dots. If we use (x, y) coordinates for the two-dimensional positions of the dots, and z-coordinates for the depths of the dots, then it is clear that for every dot in two dimensions at coordinates (x, y), there are infinitely many z's one could assign as the depth.

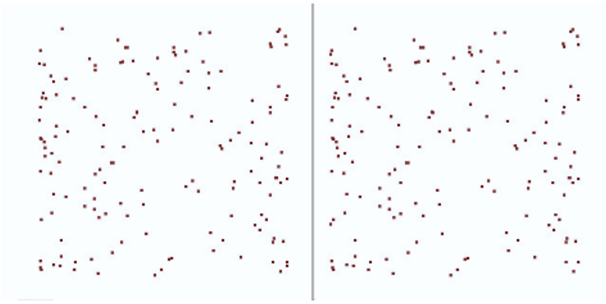


Fig. 2.3 Two frames from a film of a rotating cylinder

How does human vision pick one z-coordinate out of the infinite options that are possible? It employs certain built-in constraints. In the case of depth from motion, one constraint that roughly models the performance of human vision is rigidity. That is, human vision tries to find a rigid interpretation for the two-dimensional motions of the dots. If it can find such an interpretation, it adopts that interpretation. Ullman (1979) showed that three frames each containing four points is theoretically sufficient information for human vision, or a computer vision system, to compute successfully a rigid interpretation. If the four points are randomly positioned in the three frames, then generically it is not possible to find a rigid interpretation for the dots (see also Bennett et al 1989, Hoffman, Bennett 1986). This result is useful, for it provides a way to decide when one should not give a rigid interpretation. If the dots do have a rigid interpretation, then generically they have two rigid interpretations that are mirror images of each other. One can see these two interpretations in the Java applet by setting it in transparent mode. In this mode one will sometimes see the sphere rotating in one direction, then spontaneously reversing its direction of motion. This is a switch from one of the mathematically possible rigid interpretations to the other.

Thus our perception of depth, which is critical to successful driving, is not an objective report of the structure of the world. Instead it is a construction by the human visual system that is based on key assumptions, such as rigidity of motion. In consequence our perceptions of depth are necessarily fallible; our perceptions can be false if the assumptions on which they are based are violated. Indeed, the visual demonstrations used in this example violate the rigidity assumption: the motions of the dots are not in fact rigid.

As a consequence, our perceptions of depth in these demonstrations are incorrect. The possibility of incorrect perceptions of depth is really quite sobering in the context of driving.

Another illustration of how human vision constructs shape is the well-known Kanizsa triangle (Kanizsa 1955, 1974, 1976, 1979), two examples of which are shown below:

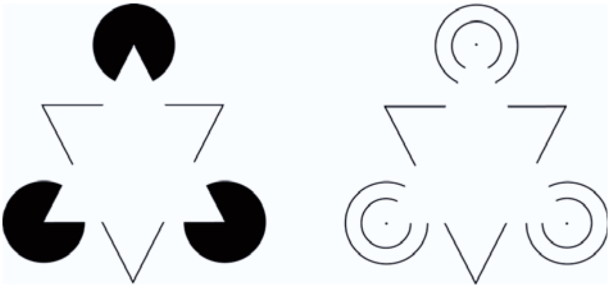


Fig. 2.4 Kanizsa's triangles. You see two white triangles with clear edges, and with interiors that appear to be a brighter white than the surroundings. In fact the triangles, including their edges and brighter interiors, are all illusory constructions of your visual system.

Perhaps you see two white triangles, each with clear borders and with a surface that appears a bit brighter than the background. Both the borders and the bright surfaces are fabrications of your visual system; if you cover the black discs and lines of the illustrations you will find that the white triangles completely disappear. Your visual system notices the precise alignment of the line endings and the gaps in the black discs, and comes up with a theory. A possible theory is that this precise alignment is simply an accident. The visual system rejects that theory and concludes that a better interpretation is that there is a triangle occluding the lines and discs, and that this occluding triangle, not mere chance, is responsible for the precise alignment of line endings and gaps. Once your visual system has reached this conclusion it then fabricates the triangle, complete with its boundaries and brighter surface. Once again we see our theories, not unadorned reality.

You might concede that we fabricate the triangles, but point out that there is certainly something about the Kanizsa illustrations that we do not fabricate, namely the black lines and discs. Thus you might conclude, we do not fabricate everything we see, only certain aspects of what we see in funny illustrations devised by pesky psychologists. But this line of reasoning is not correct. Even the black lines and discs that appear in the Kanizsa illustration are fabricated by your visual system, and are not there on the page until your visual system creates them (and the page), and puts them on the page.

This might sound impossible, but it is easy to prove. The proof lies once again in considering the structure of the retina itself. Recall that each retina has an array of many million individual photoreceptors. It is not a continuous surface. Each photoreceptor produces a signal based on the number of quanta of light it catches. So the starting point of vision is a discrete array of quantum catches that changes over time; the starting point is not continuous edges, shapes, colours, or textures. All of these must be computed from the discrete array of quantum catches. Thus the lines and discs that you see in the Kanizsa illustration are themselves the end-product of a sophisticated construction process of your visual system.

2.1.2 Constructing shading and colour

It is natural to assume that the colours and shades of grey that we perceive are not constructions of the visual system, but simply objective reports of the colours that objects in the visual world really have, whether or not we observe them. This assumption is false. Colours and shades of grey are the end products of a process of construction, a process so sophisticated that it is still not fully understood by vision researchers.

Fig. 2.5 White's illusion. The vertical grey bar on the left (behind black bars) looks darker than the vertical grey bar on the right (behind white bars). In fact as you can verify, the greys are identical. Human vision creates even the elementary sensations we have of shades of grey.

We saw a hint of this in the Kanizsa triangles, where the surface of the triangles appears to be a brighter white than the background. This extra brightness of the triangles is clearly a fabrication of the visual system, perhaps to help distinguish the fabricated triangles from their surroundings. But there are many other more compelling examples of our visual fabrication of colours and shades of grey. One example, originally conceived by White (1981), is shown in Fig. 2.5.

This illustration shows horizontal black bars against a white background, with two grey vertical bars. Look carefully at the two grey vertical bars. Are they the same shade of grey, or different shades?

It probably seems obvious to you that the bar on the right is a much lighter shade of grey than the bar on the left. But in fact exactly the same shade of ink is used to print the right and left bars. You can check this by covering up all of the illustration except for one grey patch from each of the left and right bars.

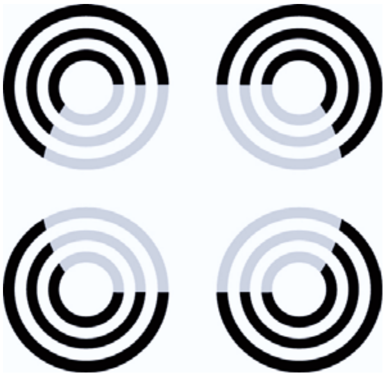


Fig. 2.6 The grey oblong. You see an oblong shape with clear borders and faint grey shading. The borders and faint grey shading are illusory constructions of your visual system. You can cover up the circles to verify this.

The grey bar on the right might also appear to float in front of the horizontal black bars, while the grey bar on the left appears to lie behind the black bars. But you can switch these perceptions. For instance, with a little effort you can see the grey bar on the right as if it lies behind horizontal white bars in front of a black background. As you switch between these two perceptions of the grey bar, notice that the quality of the grey you experience also switches. When the grey bar is seen in front of the black bars, the grey bar has a ghostly transparent appearance. When the grey bar is seen behind the white bars, it appears opaque and no longer ghostly. Here we find not only that we construct the shades of grey that we see, but that our construction of shades of grey interacts with our construction of depth, leading to the ultimately perceived qualities of our visual experience. With a little effort one can also perceive the grey bar on the left as floating in front of the black bars. Once again, the grey of the bar switches from opaque to a ghostly transparency. Another example of our construction of greys is shown in Fig. 2.6.

In this figure you probably see an oblong grey surface floating above four sets of concentric black circles. This surface appears to have a clearly defined edge all the way around it, and to be uniformly shaded on its surface. But if you cover up the concentric circles you will see that the oblong surface and its edges disappear completely. Thus the surface, its shading, and its edges are all fabrications of your visual system.

Now let us briefly consider colour. If you asked physicists to enumerate the physical properties of light, their list would include properties such as position, polarisation and wavelength. Colour would not be on the list, for colour is not a property that enters into any of the laws of physics pertaining to light.

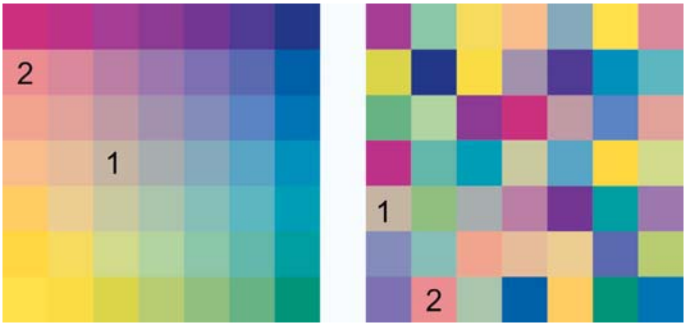


Fig. 2.7 Koenderink's squares. The left box contains 49 squares of coloured ink. The right box contains the same 49 squares of ink just randomly shuffled. Our perceptions of light sources, colouring, and three-dimensional shape on the left differ dramatically from those on the right. This shows that our colours are complex constructions of the human visual system, not simple functions of the wavelengths of light or the reflectances of surface patches.

Thus the light hitting the eye has wavelength and polarisation, but it has no colour. Colour, like shape and depth and shades of grey, is entirely a construction of your visual system. Interactive demonstrations of how you construct colours are available online at this URL:

http://aris.ss.uci.edu/cogsci/personnel/hoffman/Applets/index.html

Fig. 2.7, after one first devised by Jan Koenderink, illustrates some of the sophistication in our construction of colours. On the left is an array of

49 coloured ink squares, and on the right is the same set of coloured ink squares just randomly shuffled in their positions.

Note that on the left the squares appear to be illuminated by coloured light sources – a yellow source from the lower left, a greenish source from the lower right, and so on. Each square does not look uniformly coloured, but instead looks a little bit darker on its left side and a little bit brighter on its right side. The squares do not look perfectly flat, but appear slightly concave or convex. The colours of the squares are limited only to rainbow colours and some purples.

On the right by contrast, the squares appear to be illuminated by a single white light source rather than by several coloured light sources. Each square is uniformly coloured, rather than looking dark on the left and lighter on the right. The squares look perfectly flat rather than concave or convex. The colours of the squares are not limited to rainbow colours, but include browns and tans – colours that do not appear on the left.

This illustrates that our perception of colours is not a simple function of the wavelengths of light hitting the eye, or even of the reflectances of surface patches. Each surface patch on the left has the same reflectance function as some surface patch on the right. Yet our perception of colours (and shapes and illuminations) differs dramatically for the two identical patches.

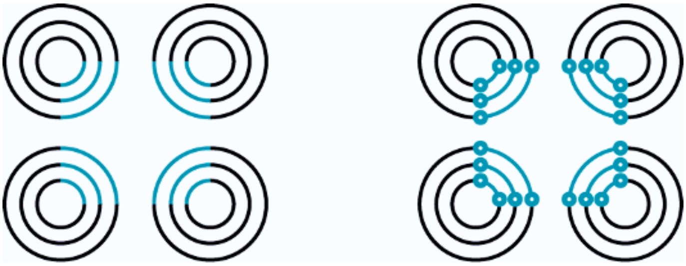


Fig. 2.8 Neon colour spreading. You see a glowing blue square on the left, with clear borders. In fact the blue square is illusory, as you can verify by covering up the circles. On the right, where we have added more blue to the figure, you have a less compelling perception of the illusory blue square. This is due to sophisticated probabilistic inferences by the visual system.

One can even construct colours in regions of the visual field that normally appear to be white. In the figure above, on the left you might see a glowing blue square with clear edges. However, the only blue ink on the page is on the blue arcs of circles. The rest of the blue square is entirely your construction. You can verify this by covering up the circles and looking at the space in the middle of the figure. If you do this, you will see that this space is white. But as soon as you uncover the circles, you will again see the glowing blue square. In the figure on the right, where small blue circles have been added, our perception of the glowing blue square is dramatically reduced. This can be explained by sophisticated probabilistic inferences employed by the human visual system (Hoffman 1998).

It appears that activity in certain regions in the lingual and fusiform gyruses of the human cerebral cortex is correlated with our visual constructions of colour. If a person has a stroke in this region of cortex in the left hemisphere, they can end up with a syndrome called hemiachromatopsia (Freedman, Costa 1992, Gowers 1887, 1888, Paulson et al 1994). They can see colour normally in the left half of the visual field, but they can only see shades of grey in the right half of the visual field. There is a fairly sharp transition from colour to greys in the middle of the visual field, at about the centre of gaze. So an apple held at arm's length would look red when the arm is in the left visual field. As the arm sweeps to the right and enters the right visual field, the apple suddenly turns grey. Sweeping the apple back to the left again restores its red colour. There are an unfortunate few people who have had strokes in this colour area on both the left and right hemispheres of the brain. They suffer from achromatopsia, a cortical inability to see colours (Collins 1925, Sacks 1995). Note that this is different from the better-known red-green colour blindness, which is not a cortical but a retinal problem, in which certain photoreceptors are missing. Some patients suffering from achromatopsia also complain that they can no longer imagine colours, or dream in colour (Sacks 1995). This is not surprising given the evidence from brain imaging studies, determining which areas of the brain are active while a person engages in different cognitive, perceptual, or motor activities. Such studies show that the same regions of the cortex that are active when seeing a visual stimulus are also active when imagining the same stimulus. (O'Craven, Kanwisher 2000). Thus we create all the colours that we see and all the colours that we imagine! Similar constructive processes are engaged in both cases.

Spotlight

Colour from motion

We see the world as containing discrete objects with specific shapes and colours. In the context of driving we see discrete objects such as pedestrians, traffic lights, buildings, and other vehicles. It might be surprising then, to learn that the image captured by the retina of the human eye contains no objects, shapes, or colours. Instead the retina reports only the number of photons captured by each of its photoreceptors. Given this array of 120 million numbers, the visual system then goes about constructing objects with specific shapes and colours. Successful construction of objects is of course critical to successful driving. In this example we consider one particularly vivid demonstration of how human vision constructs its objects.

This demonstration of the constructive power of human vision is “colour from motion” (Cicerone and Hoffman 1992) and is illustrated in an interactive applet available online here:

http://www.socsci.uci.edu/%7Eddhoff/Applets/Shadow/Shadow.html

The display shows randomly placed black and red dots against a white background. On each frame of the display certain of the black dots are switched to red, and certain of the red dots are switched to black. No dot changes position. Yet one perceives a moving red disc with a clear circular border and an interior glowing a faint red. Human vision notes the regularity with which the dots change colour from frame to frame of the display, and uses a theory to explain this regularity viz., that there is a red transparent filter passing over the black dots (Cicerone and Hoffman 1992, 1997; Cicerone et al 1995; Hoffman 1993; Wollschlaeger et al 2001, 2002). Since this theory is the best the visual system can devise, and since the visual system is quite confident about this theory, it fabricates the experience of a red filter, complete with a sharp boundary and a uniformly red interior. By altering the sliders of the applet you can change the number, colours, and size of the dots, and observe how this affects your perception of a filter. You can also get a feel for this in Fig. 2.9, which shows two frames from a film in which one sees a red transparent annulus floating over green dots. For the whole film go to:

http://www.cogsci.uci.edu/%7Eddhoff/ring168.html

Notice that the positions of the dots in the two frames shown below do not change from frame to frame. Only the assignment of colours to dots changes.

You know of course, that the theory accepted by your visual system, that of a red filter, is in fact false. But note that your knowledge does not affect your perception of the display: you still see a red filter even though you know this perception is illusory. The visual module that constructs the red filter consults a limited range of information. Your cognitive knowledge that there is no filter is not among the sources of information consulted by this module.

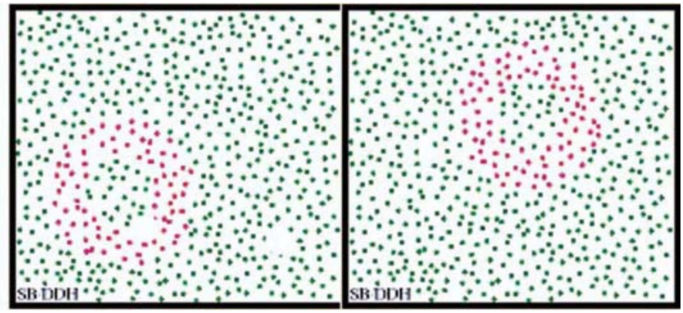


Fig. 2.9 Glowing pink ring

Why do we construct such illusory filters? Are they just curiosities that arise in certain psychology labs, but are unlikely to occur in ordinary visual perception? In fact they are not just curiosities. Instead your construction of these illusory filters illustrates a process that occurs in vision all the time. The starting point of vision is as we have discussed, a discrete array of retinal photoreceptors, and each photoreceptor reports simply how many photons of light it captures. Any time you see a continuous curve, such as the bounding curve of an object, and any time you see a continuous surface, you must construct that curve or that surface from the discrete array of information at the retina. Thus the applet discussed above is simply making starkly visible a process that is ubiquitous in visual perception, but is usually so fast and effective that it is not noticed. Similarly we don't often notice when looking at a photograph in a newspaper, that the photograph is printed as an array of small dots. Instead we automatically interpret these dots in terms of continuous curves and surfaces.

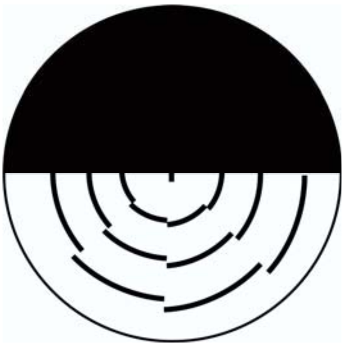


Fig. 2.10 A Benham's top

Another example for colour creation is a Benham's top. Benham's top is a simple toy. It consists of a flat disc having different areas marked in black or white, with a pin piercing the centre of the disc so that the disc can be spun on a flat surface (Fig. 2.10). The interesting thing about Benham's top is that when spinning, arcs of different colours are seen, the colours seen depending on the speed and direction of rotation. Explanations of this phenomenon have been proposed based on the relative speed of response of the different cone photoreceptors and on neural interactions in the retina and visual cortex. Whatever the explanation, it is undeniable that Benham's top demonstrates that colour is a perception generated by the visual system and not an inherent property of the radiation incident on the eye.

Benham's top is named after the English toymaker, C.E. Benham who, in 1894, first marketed the top. The phenomenon of spinning black and white stimuli being perceived to be coloured was first reported by German scientist, G.T. Fechner in 1838.

We take it for granted when we drive, that the world through which we travel contains objects. Indeed it does. But the objects you see in that world are entirely your creation. And that creation though usually useful, is nonetheless fallible. It is critical therefore, to understand the principles by which human vision creates its objects, and how automotive lighting can affect the process of object creation.

2.1.3 Constructing objects and their parts

Our visual worlds are populated by objects such as cars and people, and parts of objects, such as tires, headlights and hands. As we have discussed before, the input to the visual system is a discrete array of quantum catches; each photoreceptor reports how many quanta of light it has recently caught. This input has no colours, lines, shapes, depth or objects. Objects and their parts are a sophisticated construction of the visual system.

An example of such a construction is the ripple (Fig. 2.11) (Hoffman 1983, 1998; Hoffman and Richards 1984).

You probably see a wavy object in this illustration, much like a water wave. Of course, once again the page is flat, so the three-dimensional object you see must be constructed by your visual system. Knowing that it must be flat does not seem to stop your visual system from insisting on constructing a three-dimensional object. No matter how long you look, you are unlikely to be able to see the lines of the illustration simply as two-dimensional curves on a page. This shows that although the visual system is sophisticated in its constructions, it can also persist in an error even when presented with clear evidence of it. The visual system operates according to built-in rules, and these rules grant it its constructive powers.

However these same rules are sometimes the source of a dysfunctional inflexibility, an inability to construct a different and more useful interpretation of the visual world. Understanding these rules, with their strengths and also their inflexibilities, is important for engineers and psychologists designing automotive lighting systems. Such lighting systems cannot assume an ideally flexible observer who sees the world as a physicist would describe it. Rather they must assume an observer with sophisticated rules of construction, rules that for better or worse dictate what subjective interpretation the observer will see.

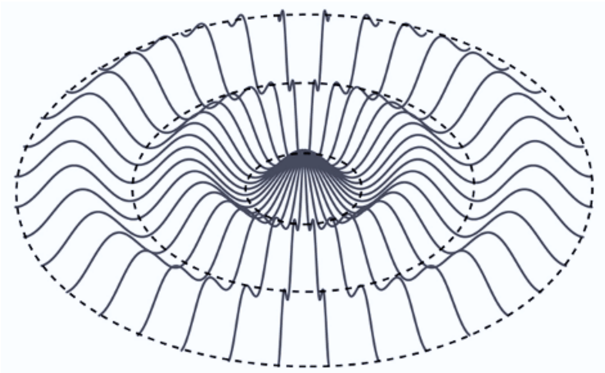


Fig. 2.11 The ripple. You see a wavy surface in three dimensions. This is an illusion, as in fact the page is flat. You also see the dashed contours as lying in the valleys between hills. But if you turn the figure upside down, you will see the dashed contours lying on top of a new set of hills that you have just created.

If you look again at the ripple you will notice that it appears to be organised into a system of three concentric parts: a hill in the middle, a ridge around the hill, and another ridge around the first ridge. I have placed a dashed circular contour on the ripple everywhere where one of these parts ends and the next one begins. These part boundaries lie, as you can see in the illustration, in the valleys between the hills and ridges.

Now turn the page upside down and look at the ripple again. You will see that your visual system has created a new organisation of the ripple into a different set of parts. The dashed circular contours which at first were in the valleys between parts, are now on the crests of the new parts created by your visual system. If you turn the page upright again you will see that you again create your original set of parts. If you turn the page on its side, you might be able to get the ripple to switch back and forth between these two sets of parts. Thus you fabricate the ripple and its three-dimensional shape, and then you embellish your fabrication by imposing on it a system of parts.

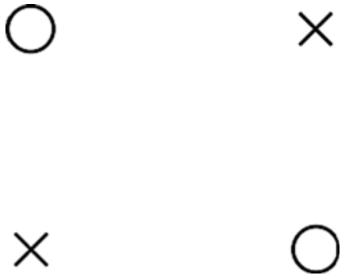


Fig. 2.12 Two frames of von Schiller's motion display. The circles indicate positions of two dots in the first frame, and the X's indicate positions of two dots in the second frame.

How you fabricate objects interacts with how you fabricate visual motions. An example of this is a display first devised by von Schiller (1933):

This figure depicts a two-frame animation in which there are only two dots visible in each frame. The positions of these two dots in the first frame are shown by circles and their positions in the second frame by X's. The two frames are shown repeatedly in a loop mode. What one sees, if the timing of the frames is properly adjusted, is shown in the next illustration:

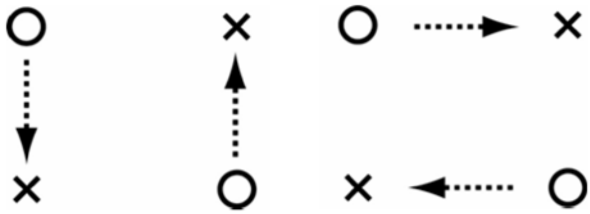


Fig. 2.13 Two different perceptions of the von Schiller display. Sometimes, as shown on the left, we see the dots move up and down. Other times, as shown on the right, we see the dots move to the left and right.

Sometimes, as depicted in the left side of this figure, one sees the two dots jumping up and down vertically, one dot on the left and one on the right. At other times, as depicted in the right side of this figure, one sees the two dots jumping side to side horizontally, one dot above and one dot below. As one watches the film, it appears to do one of these motions for a while, then flip to the other motion for a while, continuing to alternate repeatedly. But what one doesn't see is a motion of the type depicted below:

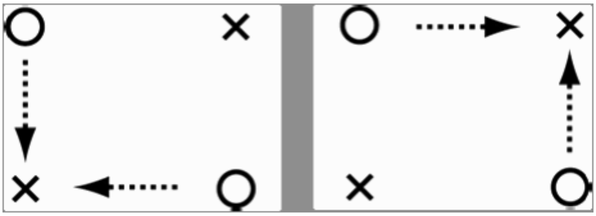


Fig. 2.14 Logically possible interpretations of the von Schiller display that we do not see. When possible we avoid, creating or destroying objects. We prefer to preserve the number of objects, and interpret them as moving.

In the motion depicted on the left of the figure, the two dots in the first frame merge into one dot in the lower left hand corner of the second frame, and a new dot appears out of nowhere in the upper right hand corner of the second frame. In the motion depicted on the right of the figure, the two dots in the first frame merge into one dot in the upper right hand corner of the second frame, and a new dot appears out of nowhere in the lower left hand corner of the second frame. In both of these cases a dot from the first frame is “destroyed” and a new dot is created in the second frame.

Human vision creates all the objects it sees, but it does not want to create needlessly or destroy objects. Hence we see the up and down motions, or the side-to-side motions, but we do not see the motions in which dots are created or destroyed. The motions we create are designed to economise on the objects we create.

There are regions in the cortex of the temporal lobe of the human brain whose activity correlates with the construction of visual objects. If one has a stroke to such a region one can suffer from “visual object agnosia”, an inability to see objects (Farah 1990; Farah and Ratliff 1994). A person might have normal visual acuity and normal colour vision, and be able to see lines and textures. They just can't put the lines, colours and textures together to construct objects. Sometimes a stroke can selectively impair one's ability to recognise faces, a condition called “prosopagnosia.” The person might be able to recognise cars, chairs, and other objects without problem, but simply cannot recognise familiar faces, even the face of a spouse or their own face seen in a mirror (Farah 1990; Farah and Ratliff 1994; Pallis 1955).

There are other regions of the brain whose activity correlates with the construction of visual motion. A stroke to one of these regions can lead to a condition called “akinetopsia,” a selective inability to see motion (Beckers and Hoemberg 1992; Beckers and Zeki 1995). The world appears rather as it would under a strobe light, where you see an object in one position and then another, but you don't see it move between the two positions.

Thus human vision constructs all the objects, motions, and parts that we see, and a stroke can unfortunately selectively destroy one aspect of the visual system's constructive capacities.

Spotlight

Why do I sometimes see flickering rear lights?

Introduction

If you see flickering rear lights on the car in front of you, this might not mean that you are drunk or that your visual perception is impaired in another unusual way. It is much more probable that the car in front of you has LED backlights which are operated in pulse-width modulated mode. The flickering typically is observed when the modulation frequency is not high enough.

Pulse width modulation of LEDs

The luminous flux of an LED can be controlled in several ways. A very common approach is to operate the LED in pulse-width mode. In this case, the electrical current is turned on and off several times per second. Due to the very fast switching time of the LED the resulting luminous flux is then also modulated with the same frequency. If the modulation frequency is high enough (above 70 Hz), our eye will only observe the time average of the luminous flux, as was first formulated by Talbot in the 19th century.

$$\overline{L} = \frac{1}{T}\int_0^T L(t)dt\,.$$

It is therefore possible to control the (time averaged) brightness of an LED simply by changing the duty ratio of the electric current supply. There are many standard topologies which can be used as pulse width modulated electric driver circuits for LEDs.

Pulse width modulated LEDs allow us to use the same light sources for brake lights and rear tail lights. In this “integrated solution” the LED is modulated at a duty cycle of say 10% for the rear position light and at a duty cycle of 100% for the brake light.

Visual perception of moving pulse-width modulated signal lamps

The problem with pulse width modulated signal lamps is that Talbot’s law applies to static situations and not to moving objects. If the signal lamp has a relative motion with respect to our retina, or if the eye has a relative motion with respect to the signal lamp, the continuous motion is mapped on discrete points on the retina as shown in Fig. 2.15. This can lead to confusing visual perceptions manifested as flickering. In extreme cases there can even be the strange impression of flashing lights at places where the signal lamp never was. This is then due to the saccades of the eye. As can be seen from Fig. 2.15 the effects become more pronounced if the duty cycle is low.

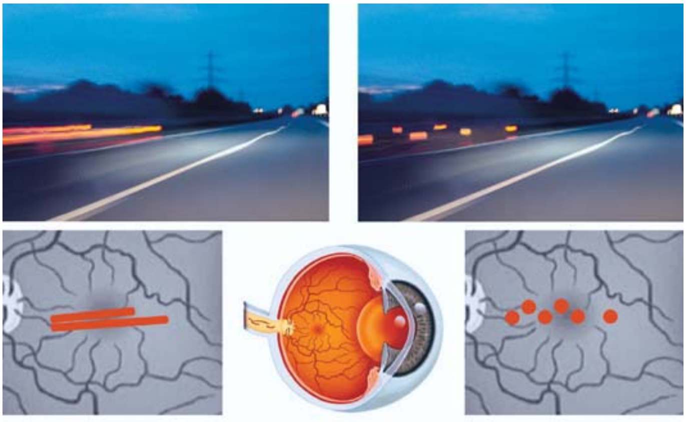


Fig. 2.15 The continuous relative motion of a signal lamp which emits a time-continuous luminous flux is mapped on a continuous path on the retina (left), while the same relative motion of a signal lamp which emits a pulsed luminous flux is mapped onto discrete points of the retina.

Conclusion

The use of pulse width modulated LEDs in signal lamps can have dramatic consequences if the modulation frequency is too low. 70 Hz, as suggested from Talbot’s law for static situations, is not sufficient. The obvious solution to operate the LED at higher frequencies has the disadvantage that it can cause electromagnetic interference with other electronic equipment.

2.1.4 Limits of attention

Human vision has limited resources of attention. Attention to one task or to one part of the visual field can leave us unaware of important events occurring elsewhere in the visual field. One remarkable example of this is an experiment by Simons and Chabris (1999) playfully called “Gorillas in our midst.” Each subject had to watch as several people passed a basketball back and forth. The subject’s task was to count the number of times the basketball was passed. In the middle of the task, a person dressed in a gorilla suit strolled among the people passing the basketball, stopped, turned to face the subject, pounded its chest, and then walked away. The gorilla was visible for about 9 seconds. Yet only 50% of the subjects ever noticed the gorilla. Their attention was absorbed with their counting task and even the presence of a potentially threatening gorilla did not get their attention. The experiment was conducted at normal room lighting levels, showing that inadequate lighting was not the problem. Raising the overall illumination in the room would not have helped to increase the percentage of subjects that noticed the gorilla. The implications for driving are obvious and worrying. A driver absorbed with one visual task or attending to one part of the visual field might be totally unaware of for example, a pedestrian that walks in front of the driver’s car. Raising the overall illumination would not help this situation. However, a highly intelligent car, able to monitor the driver’s eye movements and judge where the driver was directing his attention, could help by flashing a spotlight on the pedestrian, thus attracting the driver’s attention to the danger.

2.1.5 General principles

We have considered several concrete cases in which it is clear that human vision constructs what we see: depth, shape, lines, colours, motions, objects and shades of grey.

There are some general principles that emerge from consideration of all these special cases. The first principle is the *fundamental problem of vision* (Hoffman 1998):

- The image at the eye has countless possible interpretations.

This problem arises because the language of retinal photoreceptors is impoverished compared to the language required to describe a visual world. The language of photoreceptors is exclusively about time-changing quantum catches in a two-dimensional array; it can be thought of as a time-varying set of 120 million numbers. The language of visual worlds is far richer: colours, textures, shape, depth, objects, motions, and scenes. As a result, there are countless visual worlds one could in principle construct from any time-varying retinal image. This is the same problem that crops up in the philosophy of science. No matter how much data a scientist collects, there are always countless theories that could, in principle, account for all the data, and yet differ in their predictions on experiments not yet performed. The ambiguity of retinal images leads to a second principle, the *fundamental role of visual rules* (Hoffman 1998):

- The visual system constructs visual worlds from images in conformance to rules.

Mathematically one can think of the visual system as trying to solve an ill-posed problem. Recall that in mathematics, an ill-posed problem is one that either has no solution, or a solution that is not unique, or a solution that does not vary continuously with the inputs. When mathematicians are faced with an ill-posed problem to solve, they introduce new constraints that force a unique solution. Similarly, the visual system faces a problem that has countless solutions, so it imposes certain constraints to try to reach unique visual interpretations. These constraints are the visual rules of the second principle.

Understanding these rules is the key to understanding how human vision operates, with both its strengths and its limitations. Research into human vision has revealed dozens of rules that govern our construction of objects, light sources, colours, textures, shading, and motion (Hoffman 1998). Many of these rules are probabilistic and have led to Bayesian formulations of the constructive processes of vision. These have had great success not only in modelling human vision, but also in building effective machine vision systems (Knill and Richards 1996).

The assumption that human vision behaves like a camera, passively and accurately reporting the detailed structure of the visual environment is, as we have seen, grossly inaccurate. Instead human vision acts more like a clever detective, making inferences about the visual environment from clues in the retinal image. As a result human vision is fallible as is the best of detectives. Understanding the characteristic style of inferences employed by human vision, with all their strengths and weaknesses, is essential for the designer of automotive headlights. Otherwise there is no chance for these headlights to aid optimally the visual system in constructing visual worlds that maximise the chances for enjoyable and accident-free driving. For instance the processes by which human vision constructs the three-dimensional structure of the world from visual motion and stereo are critical to effective driving; we must see depth to drive. Fortunately, these constructive processes are associated with activity in the magnocellular pathway of the human visual system (which is described in more detail later in this chapter), a pathway that is still operational under conditions of low illumination (Livingstone and Hubel 1988). Thus, even in reduced illumination conditions human vision can often construct depth with sufficient detail to guide safe driving. In lower illumination we can also construct motion information critical to safe driving. However, the constructive processes involved in object recognition require higher illumination to be effective, thus making it more difficult for drivers to identify important objects under reduced illumination.

Spotlight

Change blindness

The eye functions in certain respects much like a camera. But there is an important proviso. In a camera the pixels populate the image plane with uniform density. But in the human eye the density raries. It is highest in the fovea (Dowling 1987). Outside the fovea, the receptor density is in general, insufficient to permit detailed representation and recognition of objects. When we look at an object, we position the retinal image of that object so that it falls on the fovea, where we have the maximum photoreceptor density and in consequence, the highest image resolution. The impression we often have, that we see the whole visual world with high acuity, is an illusion. In fact we see with high acuity only a circular region whose radius is about two or three degrees of visual angle about the point where we are looking. The rest of our visual field is seen in much lower resolution. The illusion of uniform high acuity is due to movements of the eye called saccades, which quickly place on the fovea an image of whatever object we want to see.

One consequence of the anisotropy of the retinal image can be seen in a demonstration online at this URL:

http://www.cogsci.uci.edu/%7Eddhoff/cbvenice.html

The demonstration briefly flashes up a picture, then flashes up a blank image, then flashes a modified version of the first picture where one object has been deleted, then flashes up another blank image (see Fig. 2.16 and Fig. 2.17). This sequence is repeated indefinitely, and one's task is to find the object that appears and disappears as the images flash. This task might sound trivial, but it can take a surprisingly long time to find even large changes in an image. Most of us are under the illusion not only that we see the entire visual field with high acuity but that in addition, we readily detect all changes anywhere within that visual field. The above demonstration will quickly disabuse you of the latter illusion.

In fact the two illusions are related. It is because we do not see the visual field with uniform acuity that we must attend to it one portion at a time. This leaves much of the visual field unattended (Pashler 1998). Changes that occur where we are not attending and that do not attract our attention, are usually missed (Rensink 2000a, 2000b, 2000c; Rensink et al 1995, 1997).

A change in an unattended part of the visual field can attract attention if it creates sufficient motion. Although we have poor acuity outside the fovea, we are remarkably sensitive to motion outside the fovea, and our attentional mechanisms are designed in part, to direct our attention to portions of the visual world that move or flash (Pashler 1998). This is of obvious adaptive significance. A movement in the bushes at the side might be prey or predator, and those who pay attention promptly are more likely to survive.

Fig. 2.16

Fig. 2.17

Fig. 2.16 shows a view of Venice. Fig. 2.17 shows the same view, but with one major change to the image. Can you detect the change? Most observers are surprised how long it takes to detect the difference. This is an example of change blindness, and reveals a limitation of human vision that is critical in the context of driving.

But motions do not always cooperate by occurring one at a time, and this can have tragic consequences for driving. A city road on a busy day typically displays a wide variety of movements at any one moment. A driver cannot attend to all of them. If the driver's attention is attracted to movement in one part of the road ahead, they can be temporarily blind for a critical instant to movement in another part of the road—perhaps to a pedestrian stepping into the road. This blindness can be exacerbated at dusk, when the photo-receptors of the eye must adapt to falling levels of light, and at night when lower light levels reduce visual acuity (McMurdo and Gaskell 1991; Pianta and Kalloniatis 2000; Livingstone and Hubel 1994)

It is necessary to understand the anisotropy of the human retina, the consequent need to attend sequentially to different parts of the visual field, and the unfortunate blindness to changes that this sometimes entails. Then we can intelligently design headlights that take into account these frailties of human vision, and direct the driver's attention where it is needed most. Headlights of the future could for instance, flash brighter lights on pedestrians and other potential obstacles in the road ahead, thereby directing the driver's attention to these obstacles. But if there are several such obstacles at any one time, and the headlights brighten them all simultaneously, then it is likely that the driver cannot attend to them all, and might miss the one that was most important (Rensink 2000a, 2000b, 2000c; Rensink et al 1995, 1997). If instead the headlights brighten the obstacles one at a time in sequence, the driver is more likely to see them all. One can choose this sequence if the car is equipped with a computer vision system, to reflect natural priorities: nearer objects before farther, humans before non-humans.

2.2 Models of visual perception

The visual system constructs all the objects, shapes, motions, colours and depths that a driver sees. We have already discussed several examples of visual constructions. We observed that understanding these constructive processes is important to the design of automotive lighting systems that are properly tailored to the visual needs of the driver. So far our discussion of these constructive processes has been primarily descriptive and non-quantitative. Now we discuss more rigorous mathematical models of visual constructions and visual decision-making i.e., Signal Detection Theory (SDT) and Bayesian models of vision, and then put these models in an evolutionary context.

2.2.1 Signal detection theory

Driving depends crucially on visual detection. For instance the driver must reliably detect pedestrians, traffic signs, traffic lights, bends in the road, lane markers, other vehicles and the accelerations and decelerations of other vehicles. Signal Detection Theory provides a simple, powerful and widely applicable mathematical framework for understanding and quantifying detection performance (Green and Swets 1988; Wickens 2002). We now discuss this framework.

To fix ideas, let's consider a particularly simple, but relevant detection problem. A human observer Susan, is looking down a poorly illuminated road at night. Susan's friend, wearing reflective clothing and hiding behind a tree, is 50 meters down the road. Sometimes the friend steps out from behind the tree onto the road, and then steps back behind the tree again. Susan tries to detect when the friend steps out onto the road. Every ten seconds Susan pushes one button on a computer indicating YES if Susan believes the friend stepped onto the road during the past ten seconds, and a different button indicating NO if Susan believes the friend did not. They conduct this experiment for twenty minutes, collecting 120 answers from Susan. Susan's friend also records, for each ten-second interval what the correct answer should be. By comparing Susan's 120 answers to the 120 correct answers recorded by the friend, we can determine how well Susan detected the appearance of the friend on the dark road.

SDT provides a convenient framework to analyse Susan's detection performance. First we compare each of Susan's answers to the correct answers. There are four possible outcomes, illustrated below:

Susan's answer	correct answer: yes	correct answer: no
yes	hits	false alarm
no	miss	correct rejection

Fig. 2.18 Possible types of outcomes for individual decisions in a detection experiment.

Susan could answer Yes when the correct answer is Yes. This is called a Hit. Susan could however, also answer Yes when the correct answer is No. This is called a False Alarm. Susan could answer No when the correct answer is No. This is called a Correct Rejection. But Susan could also answer No when the correct answer is Yes. This is called a Miss. Suppose that Susan's performance is as follows:

Susan's answer	correct answer: yes	correct answer: no
yes	45	40
no	15	20

Fig. 2.19 Hypothetical data for an example detection experiment.

In this case Susan has 45 Hits. In this experiment perfect performance would be 60 Hits, since the total number of cases in which the correct answer is Yes is 60. Thus Susan got 45 out of 60, or 75% of the possible Hits. In SDT this is described as a “Hit Rate” of 0.75. Susan also has 40 False Alarms. In this experiment worst performance would be 60 False Alarms, since the total number of cases in which the correct answer is No is 60. Thus Susan got 40 out of 60, or 66.7% of the possible False Alarms. In SDT this is described as a “False Alarm Rate” of 0.667. Using Susan’s Hit Rate and False Alarm Rate, SDT allows us to compute her detection ability. We now consider the framework that SDT assumes to compute these measures.

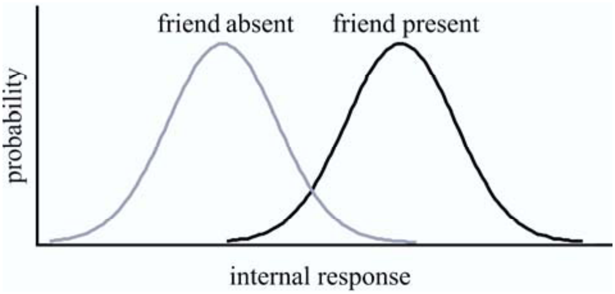


Fig. 2.20 Probabilistic constructs assumed by Signal Detection Theory. The probability of the subject’s internal state varies as a function of the visual input.

When Susan’s friend steps into the road wearing reflective clothing, this reflective clothing will scatter light in Susan’s direction so that Susan will probably have a small increment in the number of photons received at the eye. These photons lead to an internal response by Susan’s nervous system, and it is this internal response that leads to Susan’s decision. The distribution of these internal responses is represented in the figure above by the distribution labelled “Friend Present.” Susan will in general have a different distribution of internal responses when the friend is hiding. This distribution is labelled “Friend Absent.”

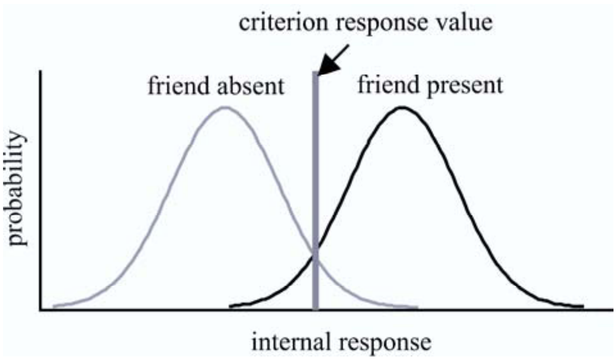


Fig. 2.21 The response criterion. If the subject’s internal response is greater than the criterion response value the subject decides Yes; otherwise No.

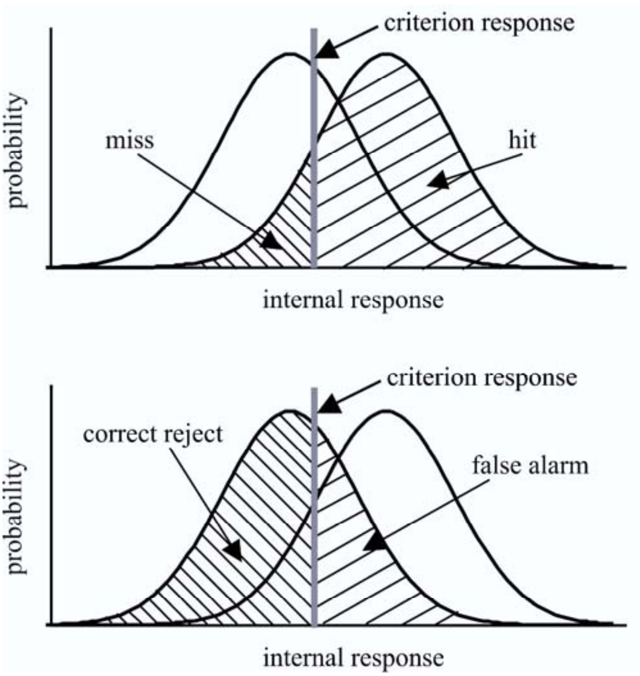


Fig. 2.22 How the response criterion, together with the distributions of internal responses determines Hits, Misses, False Alarms and Correct Rejections.

Susan must decide whether the friend was present or absent based only on Susan's internal state. Therefore Susan must employ a decision criterion. That is, if the internal state exceeds some criterion response value, then Susan answers Yes; otherwise Susan answers No. This is illustrated in Fig. 2.21.

Susan can be more conservative about saying Yes by moving the criterion response value to the right, or less conservative by moving it to the left. Such moves will alter Susan's probabilities of Hits, Misses, False Alarms, and Correct Rejections as illustrated in Fig. 2.22.

This in turn, alters Susan's Hit Rate and False Alarm Rate, as illustrated here:

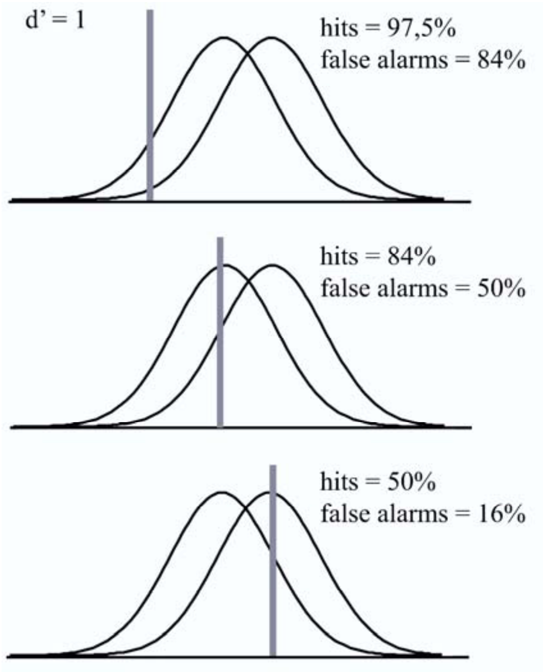


Fig. 2.23 Hit Rates and False Alarm Rates as a function of the decision criterion. Moving the criterion to the right leads to more conservative behaviour with fewer false alarms, but also fewer hits.

The probability distributions of Susan's internal states for Friend Present and Friend Absent can in principle, take on a wide range of means and variances. For instance, if the ambient light is low, then the two distributions might be quite close and have high variances. If the ambient light is high, then the two distributions might be far apart and have lower variances. If we assume that the two distributions are both Gaussian, then SDT allows us to compute a measure called d', which characterises Susan's detection ability in terms of how far apart the means of the two distributions are, as measured in units of their standard deviations. Specifically d' = z (Hit Rate) – z(False Alarm Rate), where z denotes a standard normal, i.e. $z(x) = (x - \mu)/\sigma$, and where μ is the mean and σ is the standard deviation of the Gaussian. Smaller values of d' indicate poorer detection performance. The figure below illustrates distributions with $d' = 1$ and $d' = 3$.

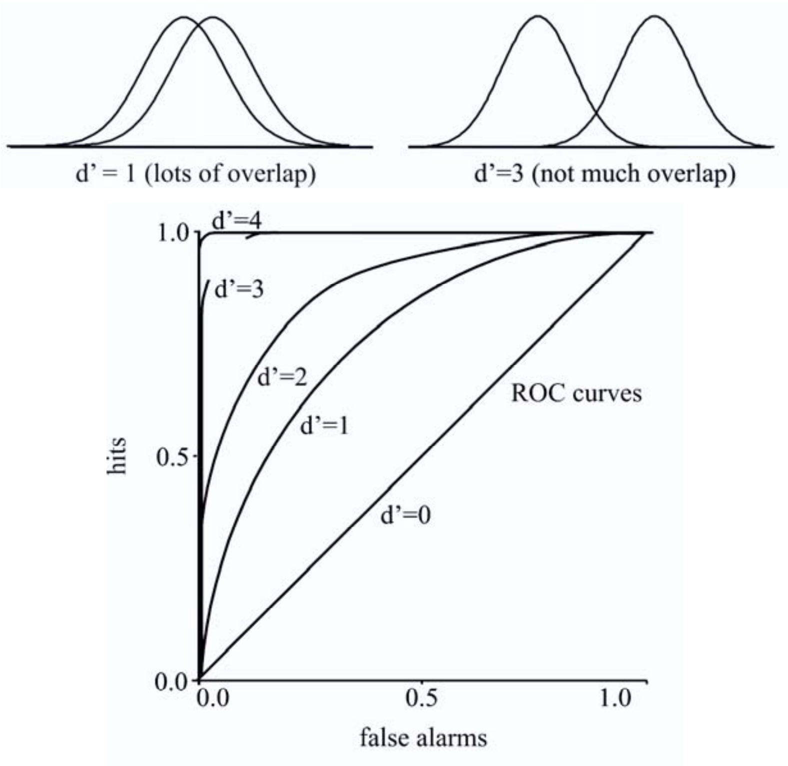


Fig. 2.24 Measuring detection performance using d′ and ROC curves. Large values of d′ indicate better detection performance. An ROC curve plots for a fixed value of d′ how Hit Rates versus False Alarm rates change, as one alters the decision criterion.

Note that Susan's detection ability i.e., Susan's value of d', is not the only variable that affects Susan's Hit Rate and False Alarm Rate. Susan's decision criterion, independent of Susan's detection ability, also affects these rates. If you fix d', and let the decision criterion vary, you can map out a curve of Hit Rates versus False Alarm Rates called a Receiver Operating Characteristic Curve or ROC curve. Several ROC curves are illustrated above for different values of d'. In the concrete example we have been considering Susan's Hit Rate is 0.75 and False Alarm Rate is 0.67. One can place the point (0.67, 0.75) in the figure above, and then determine by looking at the nearby ROC curves, what Susan's d' value is. In this case, Susan's d' is considerably less than 1, indicating very poor detection performance.

To illustrate further the implications of SDT for automotive lighting, consider the following case. Suppose you want to determine how effective a particular headlamp is for helping human drivers to identify different objects on the road ahead of them. You create an experiment in which a dark tunnel is illuminated from one end by the headlamp. A human observer sits near the headlamp and looks down the tunnel. An object is placed at the far end of the tunnel and slowly moved along the tunnel toward the observer until the observer can identify it. You record the distance at which the observer can identify the object. You repeat this same procedure many times using different objects so that you can get a reliable estimate of how far down the road the headlamp allows a human observer to have effective object identification.

Here is one (incorrect!) procedure you might decide to adopt for this experiment. You tell your observers to be very careful and not to guess what the object is until they are very sure. You tell them that on trials in which they make a mistake their data will be excluded.

Is this a reasonable procedure? Will you get a reasonable estimate of how far down the road observers can identify objects? Not at all. This procedure makes two critical mistakes. First, the decision to throw out trials in which the observer makes an incorrect choice does not allow you to separate the observer's recognition ability from their decision criterion. Second, the instructions not to guess will prompt the observer to adopt a very conservative decision criterion. As a result you will have no idea what the observer's real identification ability is, for their identification ability has been completed confounded with a conservative decision bias, and you have thrown away the data required to tease the two apart.

What you should do instead is to keep data from all trials, including trials in which the observer makes mistakes. This allows you to compute the Hit and False Alarm Rates that are required to determine d' and to determine the observer's decision criterion.

This becomes even more critical if you wish to collect data from many different observers and average the data to get a more stable estimate of the distance at which identification is reliable. Different observers will necessarily adopt different response criteria. Thus one must explicitly use the techniques of SDT to separate the effects of response criteria from true identification ability. Otherwise one will be taking an average that is not interpretable, since it is mixing data based on different response criteria. But once one has computed a d' for each observer one can then reasonably take averages to get more stable estimates.

The measure d' assumes Gaussian distributions of the internal states of the observer. This assumption is difficult to test and might, of course, be false. Can SDT be extended to apply more generally than just to the Gaussian case?

Indeed it can. One can extend SDT so that it gives estimates of detection ability that make no assumptions at all about the underlying probability distributions. The idea is to measure empirically several points on the ROC curve of an observer. Then take the area under the ROC curve, a quantity usually called A_z, as the measure of detection ability. A_z can vary from 0 to 1. Values between 0 and 0.5 indicate no detection ability. For values greater than 0.5, the higher the value the greater the detection ability, with a value of 1 indicating perfect detection ability.

There are two basic techniques for measuring empirically several points on the ROC. A key idea is that the different points on a single ROC curve correspond to different response criteria. By inducing the observer to adopt different response criteria, one can measure different points on the ROC curve. One way to do this is to change the instructions to the observers so that they adopt a more conservative or less conservative response criterion. If for instance you tell the observers that they get 2 euros for each correct detection (i.e. for each Hit) and that they are not penalised for any false alarms, then the observers will adopt a more liberal response criterion. If instead you tell them they get 1 euro for each Hit and lose 2 euros for each False Alarm, then the observers will adopt a more conservative response criterion. Thus by systematically altering the payoffs for Hits and False Alarms one can move the response criterion around and measure different points on the ROC curve.

The second technique for empirically measuring the ROC curve is to ask the observers each time they make a judgement, to give a confidence rating for their judgement. For instance the observers might be asked to rate their confidence on a scale of 0 to 5, where 0 means the least confidence and 5 means the greatest confidence. One can then use these different confidence ratings to produce different points on the ROC curve. The precise mathematical method for doing so is beyond the scope of this book, but one can find it in Snodgrass et al (1985, see also Murdock 1965), where it is called the MOC (memory operating characteristic).

2.2.2 Vision as bayesian inference

Vision is fundamentally probabilistic. The photons hitting the retina follow a Poisson distribution (e.g. Rodieck 1998). Neural signalling in the visual system of the brain is probabilistic. The final perceptual interpretation of the observer is fallible, with a real chance of being wrong. This probabilistic aspect of vision is addressed in part by the methods of Signal Detection Theory discussed above. Here we briefly mention a more comprehensive probabilistic approach to vision, based on Bayesian inference. For more details we suggest the book by Knill and Richards (1996).

We consider an observer who is given image information I. This I might be a single image, a stereo pair of images, or even a moving sequence of stereo pairs of images. In each case we will simply refer to this image information by the symbol I.

The observer wishes to make inferences about some properties designated S of the visual scene. This S might be the presence or absence of a pedestrian on the road ahead; the three-dimensional shape of the car just ahead; the speed at which the observer is driving down the road; the angle at which the road bends at the next curve; the colour of the signal light at the next intersection. In each case we will simply refer to these properties of the scene by the symbol S.

The observer wishes to make inferences about S from the information I. Probabilistically we can describe the observer's goal as determining the conditional probabilities $\Pr(S / I)$. In general, the true values of these conditional probabilities are not immediately obvious and some computation is required to obtain them. For this purpose Bayes' rule is useful. Recall that this rule states that:

$$\Pr(S \mid I) = \Pr(I \mid S) \Pr(S) / \Pr(I)$$

In Bayesian terminology the desired conditional probability $\Pr(S \mid I)$ is called the *posterior distribution*, the term $\Pr(I \mid S)$ is called the *likelihood function*, and the term $\Pr(S)$ is called the *prior distribution*. The term in the denominator $\Pr(I)$ can be viewed as a normalising factor that makes the posterior distribution take values between 0 and 1, thus making it a true probability.

The likelihood function $\Pr(I \mid S)$ can be thought of here as an image rendering function. It gives the probabilities of various images I given the values S of certain scene properties. By mathematically describing the scene properties S and mathematically describing how these properties are projected onto images I, one can compute $\Pr(I \mid S)$ precisely. As a simple example, suppose that S is the three-dimensional coordinates of n feature points $F_1, \ldots, F_n$, where the coordinates of F_i are given by $F_i = (x_i, y_i, z_i)$. Suppose that the image projection function p is noise-free orthographic projection, so that $p(x_i, y_i, z_i) = (x_i, y_i)$. Then $\Pr(I \mid F_i)$ is the Dirac measure on $p(F_i)$, i.e. a probability measure that gives a value of 1 to the point $p(F_i)$ and to any event containing $p(F_i)$ and the value 0 to all other events. If the image projection process involves in addition unbiased Gaussian noise G, with standard deviation σ, then $\Pr(I \mid F_i) = G(p(F_i), \sigma)$.

The term $\Pr(S)$ can be thought of here as the prior assumptions or constraints that the human observer uses to create its visual interpretations of the world. For instance, some possible prior assumptions that have been discussed in the vision literature include assumptions such that objects move rigidly, light sources move slowly, light sources are overhead, and the eye views the world from a generic position. Recall our earlier discussion of the fundamental problem of vision: the image at the eye has countless possible interpretations. The prior assumptions $\Pr(S)$ are critical in pruning the set of possible interpretations.

The prior distribution and likelihoods together allow the visual system to compute the posterior distribution $\Pr(S \mid I)$. Once this distribution has been obtained there still remains the problem of picking a single interpretation for the scene. The exception, which is rare, is a posterior distribution which is a Dirac measure on a single interpretation for the scene. If the posterior is not a simple Dirac measure, then the observer must employ some decision rule to pick a unique interpretation. There are many possibilities. One can simply take the maximum value of the posterior distribution, a choice known as the maximum a posteriori (MAP) estimate. One can choose the minimum mean squared error (MMSE) estimate. Or if one has a utility function or loss function available, one can choose the interpretation that maximises utility or minimises loss (see e.g. Freeman and Brainard 1995).

When researchers in computer vision want to build working vision systems that can for instance “see” in three dimensions using stereo, shading, or motion information, they often use a Bayesian analysis, for it leads to robust solutions that can be made to work in practice. For more details a good source is Knill and Richards (1996).

Thinking about visual perception as Bayesian inference is a good antidote to the misconception that vision is like a camera, that it gives simple objective reports. The Bayesian approach to vision makes us realise that our visual perceptions depend critically on the prior assumptions that our visual systems bring to the process. They also depend critically on the decision strategies and models of image formation that our visual systems employ. Ultimately, if we wish to design lighting which most intelligently facilitates the operation of human vision, we must understand its priors, likelihoods, posteriors, utility functions, and loss functions.

2.2.3 Vision, evolution, and user interface

When thinking about the design of intelligent automotive lighting and its effects on human vision, it is helpful to keep in mind the role of evolution in shaping our perceptual systems (e.g. Pinker 1997).

The neo-Darwinian account of evolution based on the notion of survival of the fittest, involves three key ingredients: variation, retention, and selection. Random mutations and sexual reproduction are key sources of variation. They guarantee that the genetic constitution of each offspring is overall, slightly different from that of its parents. Sexual (and asexual) reproduction is also the key source of retention. It guarantees that the genetic constitution of each offspring is overall, substantially like that of its parents, although it differs slightly. The environment is the key source of natural selection. Those organisms whose functional properties are best adapted to the environment have a higher probability of surviving long enough to reproduce. In consequence, their genes have a higher probability of being represented in the next generation.

A key point to note about the neo-Darwinian account is that the selection criterion is reproductive success. It is the sole selection criterion. Organisms might have substantial changes over generations in aspects of their genetic constitution that have no consequences for reproductive success. Such changes will not themselves be subject to selection. The result is genetic drift; more or less random drifting of the genetic constitution that is irrelevant to reproductive success.

The implications of this account for the evolution of the visual system are intriguing. The only selection pressures in the evolution of the visual system arise from its effects on reproductive success. Organisms whose visual perceptions guide adaptive behaviours, i.e. behaviours that are more likely to lead to reproductive success, are more likely to have offspring.

These offspring are more likely to inherit visual systems that, like those of their parents, guide adaptive behaviours.

It is easy to read into this evolutionary account more than is warranted. In particular, it is easy to read into it the idea that visual perceptions are selected based on objective fact (see, e.g. Palmer 1999, p. 6 for an example of this mistake). This is an elementary misunderstanding of the neo-Darwinian theory. It does not claim that selection is based on truth; it claims that selection is based on reproductive success. Period.

To fix ideas here, it is helpful to think of the cockroach. It has very adaptive visually guided behaviours: flee light, scurry towards dark. We are much less tempted to impute truth, or insight, to the perceptions of the cockroach. Homo sapiens, according to the neo-Darwinian account is another species, like the cockroach, whose perceptions have been shaped by one criterion only: reproductive success. There were no selection pressures towards truth, only to reproductive success within our environmental niche.

This has interesting consequences. Cars were not until very recently part of the niche in which our visual systems evolved. It should be no surprise therefore, that our visual systems might in certain respects be ill-adapted to the new perceptual challenges that face a driver. The visual system is not a perfect camera, faithfully giving a true and exhaustive description of the external world. The visual system is a fallible and opportunistic system, adapted to guide our behaviours in a specific niche. In consequence it must necessarily, have limitations and blind spots, particularly to those aspects of the world that have been irrelevant to reproductive success up to now. As designers of automotive lighting, it is critical to think of vision not as a reliable purveyor of truth, but as a fallible system with limitations tied to the niche in which it evolved. If we don’t seek out and thoroughly understand the fallibilities and limitations of the visual system, we will not be in a position to devise intelligent lighting systems that compensate as much as possible for these limitations.

Conversely, because it is adapted to a particular niche, the visual system also has remarkable strengths. We would be well advised in our development of intelligent automotive lighting and display systems to understand these strengths and to cater for them. So for instance, human vision has developed highly specialised visual pathways for the analysis of the identity and expressions of faces. This is a consequence of our niche: we spend more time viewing faces than any other objects, and proper interpretation of faces is critical to our survival and reproductive success. The face is a complex three-dimensional structure that changes rapidly in time. The amount of information per unit of time that a face contains is enormous, a fact that becomes more readily evident when one tries to electronically transmit facial information in real time for effective long-distance teleconferencing. The bandwidth required is quite large. Yet human vision readily interprets dynamically changing faces with apparent ease. We effortlessly infer from faces information about age, gender, race, health, direction of gaze, and nuances of attentional and emotional states. All of this multidimensional information about faces is processed in parallel by a high-bandwidth subsystem of the visual system that engages hundreds of millions of neurons, and many billions of synapses.

Thus, if we have complex, multidimensional time varying data that we need to communicate quickly to a human user, there is no higher bandwidth channel to the human brain for this purpose than facial stimuli. Data that would take considerable time and cognitive effort to understand if presented in other formats can be quickly and effortless understood if encoded into the structure and motion of a face.

There is an interesting, and important proviso here. A major cortical structure in the processing of facial identification is the so-called “Fusiform Face Area” (FFA), located on the underside of the brain (i.e., ventrally) near the back (i.e. occipitotemporal region), especially in the right hemisphere (Kanwisher 1997). It is unfortunately not uncommon that a stroke can damage the FFA. The person suffering such a stroke can be normal in every respect—normal acuity, colour perception, object recognition, intelligence, and so on—but with one remarkable exception: the person can no longer recognise faces. Even the face of their child or spouse, or their own face seen in a mirror, cannot be recognised. This unfortunate condition is called prosopagnosia. The prosopagnosic can still recognise people by their voices, but not by viewing their faces. The high bandwidth face-processing module, which most of us normally take for granted, has been damaged. Suddenly it becomes apparent just how much work the FFA does, and how much we rely on it.

Remarkably, a person with prosopagnosia can often still interpret facial expressions, even though they cannot identify faces. A separate cortical area, the superior temporal sulcus (STS), appears to be involved in the processing of dynamic information about the face, information critical to inferences about attention and emotion (Hasselmo 1989, Heywood, Cowey 1993, Perrett et al 1991). A stroke to the STS can leave a person unable to recognise facial expressions, even though they can identify faces.

Thus, in designing intelligent automotive lighting and displays, we must recognise that a small fraction of the population do not have this high-bandwidth channel for facial processing available to them, and that any information we encode in a facial format might not be interpretable by them.

Since evolution shapes perceptions not for truth but to guide adaptive behaviour in a particular niche, a useful way to think about our visual perceptions is in terms of a user interface (Hoffman 1998). Think for instance, of the Windows interface on your desktop PC. Suppose you are editing a file for a report that you must submit. The icon on your screen for that file might be blue and rectangular and in the lower right hand corner of your screen. But of course you are not thereby led to presume that the file itself is blue and rectangular and in the lower right hand corner of the computer. The colours, shapes, and positions of the icons on your screen are purely conventional, and are not intended to resemble the actual software and hardware in the computer that they represent. Indeed, the reason we have a Windows user interface is because it does *not* resemble all the complexity of the hardware and software of the computer, but instead hides all that complexity and gives us simple icons that usefully guide our behaviour. If we had to deal with the diodes, resistors, and voltages of the computer directly, we could never complete our report.

The shapes, colours, objects, depths, motions and shading that we perceive through vision are simply aspects of a user interface evolved by *homo sapiens* to survive in its niche without having to deal directly with reality in all its complexity. Each species has its own species-specific user interface. Each interface has its strengths and limitations. Each is to varying degrees, adapted to its niche.

When we devise intelligent automotive lighting and displays for drivers, we are in fact providing information to a system, the human observer, which has a particular user interface. To provide information to that user interface most reliably and quickly, we must make sure that the information is formatted in a manner appropriate to the user interface. And to do that, we must take care to understand that interface. We have described some aspects of that interface already. In the next sections we provide more details.

Spotlight

Information take-rate

When we hear or see something for the first time, we obtain novel information. If we hear or see it again, it has lost novelty. Information does not grow with repetition. Repeating will make information lose significance. Information is defined as the quotient between innovation and redundancy. When investigating visual processes in the context of driving then, it is worthwhile to get some idea on how much information an average driver can take in and digest whilst driving.

History

Traffic signs provide the driver with information on whether to stop or go, which way to turn and how to adjust the speed of the vehicle. Many of the graphic symbols used for signs have a long history and have been shaped by our culture. For example there is good reason to believe that the traffic sign has evolved out of the signs outside pubs and taverns in the middle ages that indicated the type of wine on sale: red for red wine, yellow for white wine and green for the freshly brewed and sweetened wine (Götz 1994).

Cultural conditioning

Repeatedly used graphical symbols have a habit of evolving with our culture. They change from complicated images into simple symbols. This is no coincidence.

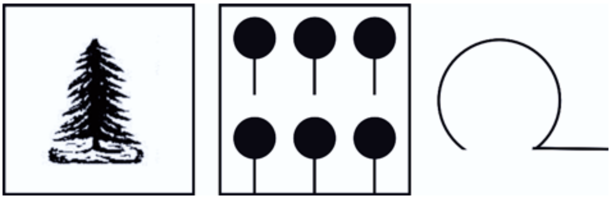


Fig. 2.25 Evolution of graphemes

A symbol that is commonly used will convey the same meaning even if it appears with marginal changes. Leaving out detail is not vital and over time the symbols are simplified without any loss of meaning. The continual evolution of graphemes enables a culture to develop a communal understanding of written language and also road signs.

Recognition speed in a man-made world

From research in graphics and communication (Stankowski, Duschek 1994) we know that graphic designers are taught to respect the consumers' limitation in visual recognition. Under the very ideal test conditions described in the research, the recognition speed for symbols can be quantified and shows that volume and complexity of information is limited to a maximum of approximately 16 units/sec. For instance a simple graphical message can be picked up within 1/10 to 1/5 of a second. A more continuous stream of 8-10 units per second is still manageable for the average observer without suffering from information overload. The experimental environment used cannot be translated directly to driving. It does however have subtle implications for the man-made environment.

Visual comfort versus information overload

The situation for driving is not dissimilar. Many of the objects relevant for driving are man-made. Road markings and signs demand the driver's attention. Information provided to drivers by displays may challenge their visual capacity. Hence care needs to be taken in laying out the visual environment if we want to make driving a stress-free and comfortable occupation.

Fig. 2.26 Visual comfort

Fig. 2.27 Information overload

2.3 Visual structure and capabilities

The human visual system is much more than just the eye. Rather, it is the eye and brain working together. Despite this fact, the obvious starting point for a consideration of the visual system is the eye.

2.3.1 The physiology of vision

The structure of the eye

Fig. 2.28 shows a section through the eye, the upper and lower halves being adjusted for focus at near and far distances respectively. The eye is basically spherical with a diameter of about 24 mm. The sphere is formed from three concentric layers. The outermost layer called the sclera, protects the contents of the eye and maintains its shape under pressure. Over most of the eye's surface the sclera looks white, but at the front of the eye the sclera bulges up and becomes transparent. It is through this area, called the cornea, that light enters the eye. The next layer is the vascular tunic or choroid. This layer contains a dense network of small blood vessels that provide oxygen and nutrients to the innermost layer, the retina. As the choroid approaches the front of the eye it separates from the sclera and forms the ciliary body. This element produces the watery fluid that lies between the cornea and the lens, called the aqueous humour. The aqueous humour provides oxygen and nutrients to the cornea and the lens, and takes away their waste products. Elsewhere in the eye blood performs this function, but on the optical pathway through the eye a transparent medium is necessary.

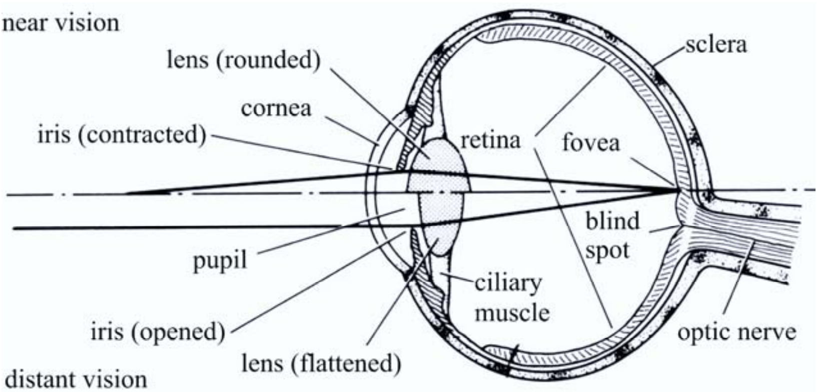


Fig. 2.28 A section through the eye adjusted for near and distant vision

As the ciliary body extends further away from the sclera it becomes the iris. The iris forms a circular opening called the pupil, which admits light into the back of the eye. Pupil size varies with the amount of light reaching the retina, but it is also influenced by the distance of the object from the eye, the age of the observer and by emotional factors such as fear, excitement and anger (Duke-Elder 1944).

After passing through the pupil, light reaches the crystalline lens. The lens is fixed in position, but varies its focal length by changing its shape. The change in shape is achieved by contracting or relaxing the ciliary muscles. For objects close to the eye the lens is thickened. For objects far away the lens is flattened.

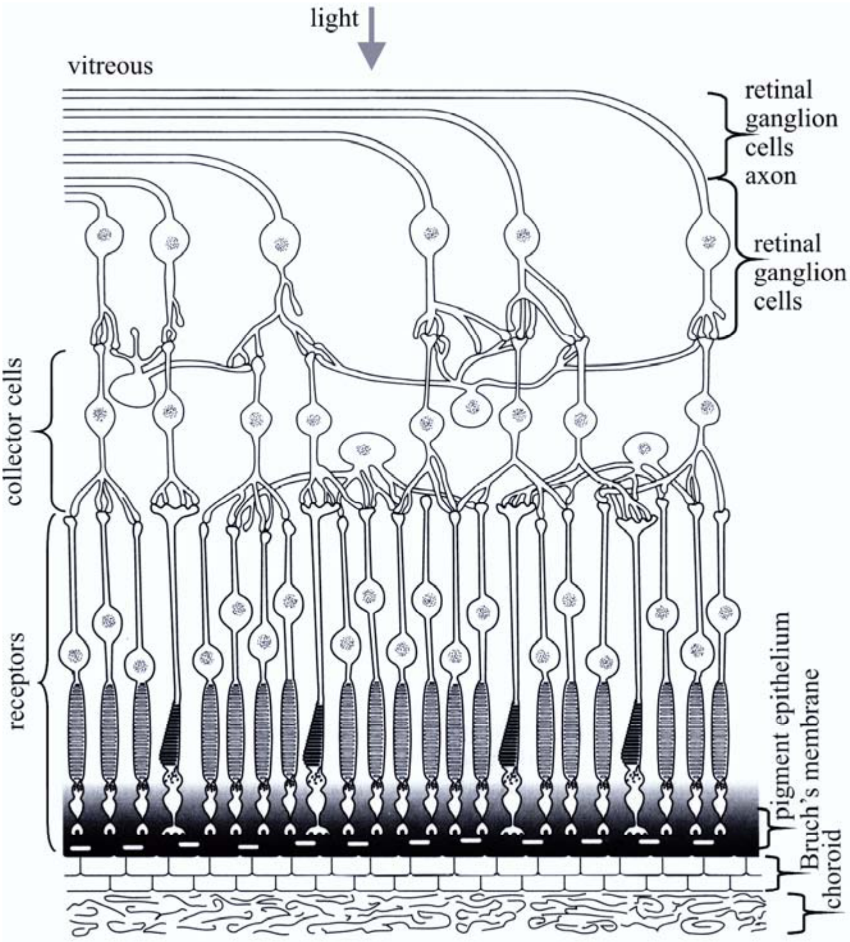


Fig. 2.29 A section through the retina (after Sekular and Blake 1994)

The space between the lens and the retina is filled with another transparent material, the jelly-like vitreous humour. After passing though the vitreous humour light reaches the retina, where light is absorbed and converted to electrical signals. The retina is a complex structure (Fig. 2.29). It can be considered as having three layers: a layer of photoreceptors, a layer of collector cells which provide links between multiple photoreceptors, and a layer of ganglion cells. The axons of the ganglion cells form the optic nerve which produces the blind spot where it passes through the retina out of the eye. Light reaching the retina, passes through the ganglion and collector cell layers before reaching the photoreceptors, where it is absorbed.

Any light that gets through the photoreceptor layer is absorbed by the pigment epithelium.

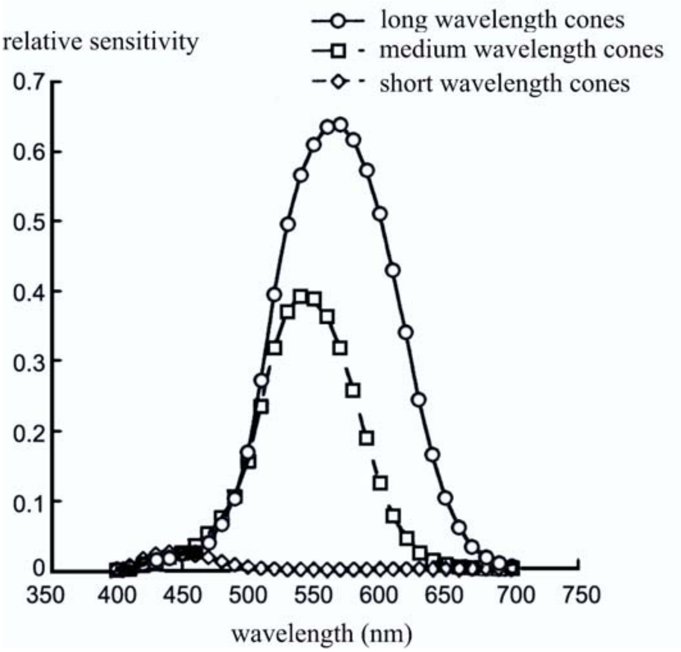


Fig. 2.30 The relative spectral sensitivities of long wavelength (L), medium wavelength (M) and short wavelength (S) cone photoreceptors (after Kaiser and Boynton 1996)

The structure of the retina

The eye is sometimes thought of as a camera. A camera has a fixed image distance, an adjustable lens and a variable aperture, as does the eye. A camera has a film, whereas the eye has the retina- which is nothing like a film. The retina is an extension of the brain. It derives from the same tissue as the brain, and as in the brain damaged cells are not replaced. The visual system has four photoreceptor types in the retina, each containing a different photo pigment and hence having a different spectral sensitivity. These four types are conventionally grouped into two classes - rods and cones. All rod photoreceptors are the same, containing the same photo pigment and hence having the same spectral sensitivity. The other three photoreceptor types are all cones, each with a different photo pigment. Fig. 2.30 shows the relative spectral sensitivity functions of the three cone photoreceptor types, called short, medium and long wavelength cones after the wavelength region where they have the greatest sensitivity.

Rods and cones are distributed differently across the retina (Fig. 2.31). The cones are concentrated in one small area that lies on the visual axis of the eye, called the fovea, although there is a low density of cones across the rest of the retina.

The three cone types are also not distributed equally across the retina. The L- and M-cones are concentrated in the fovea, their density declining gradually with increasing eccentricity. The S-cones are largely absent from the fovea, reach a maximum concentration just outside the fovea and then decline gradually in density with increasing eccentricity.

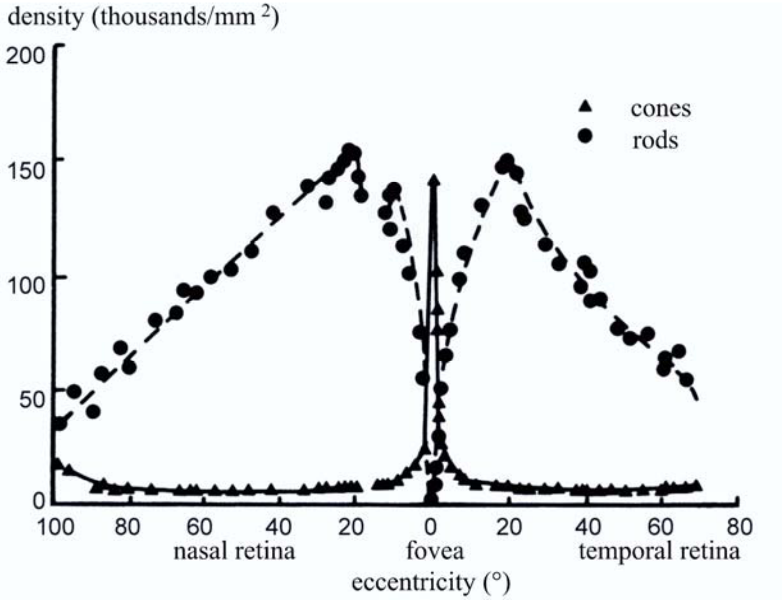


Fig. 2.31 The distribution of rod and cone photoreceptors across the retina. The 0 degree indicates the position of the fovea.

Over the whole retina there are many more rods than cones, approximately 120 million rods and 8 million cones. The fact that there are many more rod than cone photoreceptors should not be taken to indicate that human vision is dominated by the rods. It is the fovea that allows resolution of detail and other fine discriminations. The fovea is entirely populated by cones. There are three other anatomical features that emphasize the importance of the fovea. Firstly blood vessels are absent. Over most of the retina light passes through a network of blood vessels before reaching the photoreceptors. But blood vessels avoid crossing over the central area of the retina called the macula, at the centre of which is the fovea. Secondly even the collector and ganglion layers of the retina are pulled away over the fovea. This helps reduce the absorption and scattering of light in the region of the fovea and thus enhances the resolution of detail. Thirdly the outer limb of each cone photoreceptor can act as a wave guide, making cones most sensitive to light rays passing through the centre of the lens (Crawford 1972). Known as the Stiles-Crawford effect, this characteristic compensates to some extent for the poor quality of the eye's optics, by making the fovea less sensitive to light passing through the edge of the lens or scattered in the optic media. The fovea is populated only with cones. Rod photoreceptors, which dominate the population of the rest of the retina, do not show a Stiles-Crawford effect.

The operation of the retina

The retina is where the processing of the retinal image begins. Light arrives at the retina in the form of photons. The absorption of photons in a photoreceptor modifies the electrical discharges produced by the photoreceptor. Studies of the pattern of electrical discharges from a single ganglion cell have revealed two important aspects about the operation of the retina. The first is the existence of receptive fields. A receptive field is the area of the retina that determines the output from a single ganglion cell. A given receptive field always represents the activity of a number of photoreceptors, and often reflects input from different cone types as well as from rods. Firstly the sizes of receptive fields vary systematically with retinal location. Round the fovea they are very small. As eccentricity from the fovea increases so does receptive field size. Secondly the sensitivity of a receptive field to light is primarily determined by its size. All ganglion cells require some finite minimum electrical input to be stimulated. Thus a receptive field receiving input from a large number of photoreceptors can be stimulated by a lower retinal irradiance than can a receptive field receiving input from only a few photoreceptors. Hence the sensitivity to light of small receptive fields is usually significantly less than that of larger fields. The rod photoreceptors are concentrated outside the fovea and are organised into relatively large receptive fields. This makes the rod photoreceptor system significantly more sensitive to light than the cone photoreceptor system.

While every retinal ganglion cell has a receptive field, the ganglion cells are not identical. There are in fact two types of ganglion cell, called magnocellular (M) cells and parvocellular (P) cells. There are a number of important differences between the M and P cells. Firstly the axons of the M-cells are thicker than those of the P-cells, indicating that signals are transmitted more rapidly from M-cells than from P-cells. Secondly there are many more P-cells than M-cells, and they are distributed differently across the retina. The P-cells dominate in the fovea and parafovea, the M-cells dominate in the periphery. Thirdly, for a given eccentricity the P-cells have smaller receptive fields than the M-cells, explaining some of the local variation in receptive field size with eccentricity. Fourthly the M-cells and P-cells are sensitive to different aspects of the retinal image. The M-cells are more sensitive to rapidly varying stimuli and to small differences in illumination, but are insensitive to differences in colour. The P-cells are more sensitive to small areas of light and to colour.

This brief description of the retina is enough to confirm that the retina is not at all like a film. The retina extracts information on boundaries in the retinal image and then extracts specific aspects of the stimulus within the boundaries such as colour and texture. These aspects are transmitted up the optic nerve, formed from the axons of the retinal ganglion cells, along different channels.

The central visual pathways

Fig. 2.32 shows the pathways over which signals from the retina are transmitted. The optic nerves leaving the two eyes are brought together at the optic chiasm. At the optic chiasm the optic nerve from each eye is split, and parts of the optic nerves from the same side of the two eyes are combined. This arrangement ensures that the signals from the same side of the two eyes proceed together.

The signals from the same side of the two eyes pass from the optic chiasm to one of the lateral geniculate nuclei. During this passage, some optic nerve fibres are diverted to parts of the brain responsible for such diverse functions as eye movements, the instinctive fear response and the entraining of the human circadian system- but most go to one of the lateral geniculate nuclei. Anatomically, a lateral geniculate nucleus shows six distinct layers. Two of these layers receive signals from the M-ganglion cells of the retina while the other four layers receive signals from the P-ganglion cells. Each layer is arranged so that the location of the M-cells and P-cells on the retina is preserved. The division of function found in the retina is also present in the lateral geniculate nuclei. The magnocellular layers do not respond to colour differences. This is the task of the parvocellular layers. Indeed, some receptive fields show strong responses when the centre is illuminated by one colour and the surround by another. The specific colour combinations being red and green or yellow and blue, this being the basis of human colour vision. The receptive fields in the parvocellular layers are smaller than in the magnocellular layers, so the parvocellular layers will be better at resolving detail; but the magnocellular layers will respond faster to a change in the amount of light.

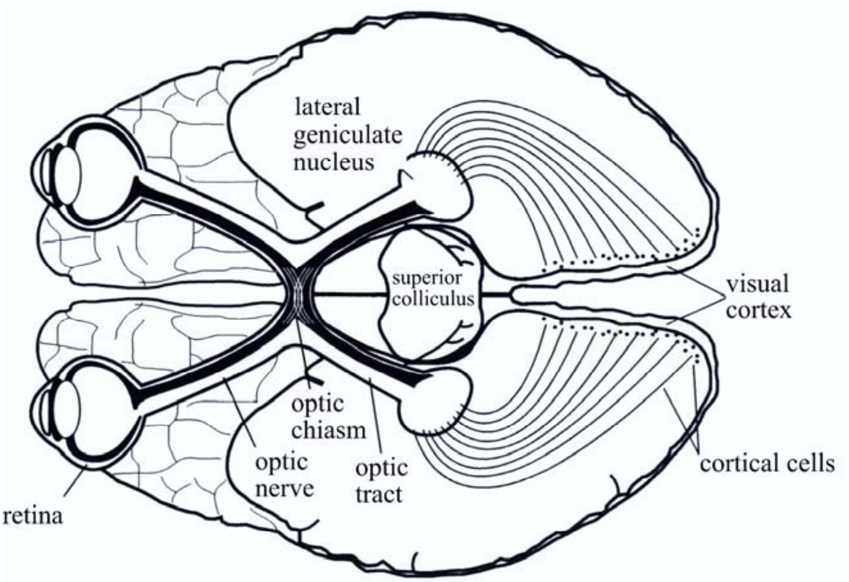


Fig. 2.32 A schematic diagram of the pathways from the eyes to the visual cortex (from IESNA 2000)

After the lateral geniculate nuclei the two optic nerves spread out to supply information to various parts of the visual cortex. The visual cortex is located at the back of the cerebral hemispheres. It consists of another layered array of cells, containing about 1 million cells. Apart from its amazing complexity, it is remarkable for the similarity of its organisation to that of the retina and the lateral geniculate nuclei. For example, the magnocellular and parvocellular channels remain separated, signals from the magnocellular layers of the lateral geniculate nuclei are received in one layer of the visual cortex, while signals from the parvocellular layers go to another. Furthermore, each cortical cell reacts only to signals from a limited area of the retina, and the arrangement of the cortical cells replicates the arrangement of ganglion cells on the retina. Moreover, the number of cortical cells allocated to each part of the retina enhances the importance of the fovea. In a phenomenon called cortical magnification about 80% of the cortical cells are devoted to the central ten degrees of the visual field (Drasdo 1977), the centre of which is the fovea. There is considerable diversity in the response of the cortical cells. Some cortical cells show sensitivity to the orientation of a boundary. Yet others respond strongly to a moving boundary of the appropriate orientation. Some cortical cells show no sensitivity to boundary orientation but are very sensitive to colour differences. Yet other cortical cells respond more to signals from the left eye and others to the right eye, while some respond equally to signals from both eyes. All this diversity of response occurs at the entry level of the visual cortex. There is a far more complex structure beyond this in the higher areas of the visual cortex. Investigation of these areas has shown that different parts of the visual cortex are dedicated to specific discriminations. For example, areas have been identified in the visual cortex that are concerned with analysing colour, motion and even human faces viewed from particular angles (Desimone 1991). A review of the operation of the visual system starting from the higher levels of the visual cortex is given in the preceding essay.

Colour vision

Human colour vision is trichromatic i.e. it is based on the three different cone photoreceptors. These photoreceptors are characterised by different wavelengths for peak sensitivity, but all have broadband spectral sensitivity with considerable overlap (Fig. 2.30). The number of photoreceptor types used to form a colour system is a matter of compromise. A single photoreceptor type containing a single photo pigment is unable to discriminate differences in wavelength from differences in irradiance, and therefore does not support colour vision e.g. rod photoreceptors. A system with many different photoreceptors each containing a different photo pigment would be able to make many discriminations between wavelengths, but at the cost of taking up more of the neural capacity of the visual system.

The outputs from the three cone photoreceptor types are believed to be arranged into one non-opponent achromatic system and two opponent chromatic systems. The achromatic channel receives inputs from the M- and L-cones only. The red-green opponent chromatic channel produces the difference between the output of the M-cones and the sum of the outputs of the L- and S-cones. The other opponent chromatic channel, the yellow-blue channel, produces the difference between the S-cones and the sum of the M- and L-cones. The non-opponent channel always gives an increase in activity with increasing retinal irradiance. The opponent channels can show either an increase or a decrease in activity depending on the wavelength of the incident light. The achromatic information is transmitted to the visual cortex by the magnocellular channel, while the chromatic information proceeds via the parvocellular channel.

The ability to discriminate the wavelength content of incident light makes a dramatic difference to the information that can be extracted from a scene. Creatures with only one type of photo pigment i.e. those without colour vision, can only discriminate shades of grey from black to white. Approximately 100 such discriminations can be made. Having two photo pigment types increases the number of different combinations of irradiance and spectral content that can be discriminated to about 10,000. Having three types of photo pigment increases the number of discriminations to approximately 1,000,000 (Neitz et al 2001). Thus colour vision is a valuable part of the visual system and not a luxury which adds little to utility. Unfortunately this value is most evident during daytime and serves to emphasise that man has evolved as a diurnal rather than a nocturnal creature.

Summary

It should now be clear that the visual system consists of three parts: an optical system that produces an image of the outside world on the retina of the eye; an a image processing system that extracts different aspects of that retinal image at various stages up the optic nerve, while preserving the location of the information; and a very subtle modelling process that combines the incoming information with what has been experienced previously, to generate a model of the world around us.

It should also be clear that the visual system devotes most of its resources to analysing information from the central area of the retina, particularly the fovea. This implies that peripheral vision is mainly devoted to detecting something that should be examined in detail by turning the head and eyes so that the image of whatever it is falls on the fovea.

One other point that should be appreciated is that the visual system is not fixed in time. On a short time scale, the visual system makes continuous, unconscious adjustments to optimise its capabilities depending on the amount of light available. These will be discussed next. On a much longer time scale the capabilities of the visual system, like those of all biological systems, deteriorate with increasing age. The nature of these changes is discussed elsewhere.

Spotlight

The closed loop: Driver – Car

The human driver himself has to be described by technical terminology when explaining the interaction between driver and vehicle using scientific methods. The goal is to simulate the interaction in order to improve it by appropriate design. The paradigm of the closed loop is especially suitable for this description. The closed loop serves generally as a basic scheme of ergonomics (see Schmidtke 1993; Helander 1988; Bubb 1993; and Fig. 2.33). In the 40's and 50's of the last century the modelling of the human operator using control theory had their origin in the cybernetics of Wiener (1948) and Shannon (1949). This gave rise to optimism about finding a natural scientific treatment of human information-processing close to the methods of physics (Jürgensohn 1997).

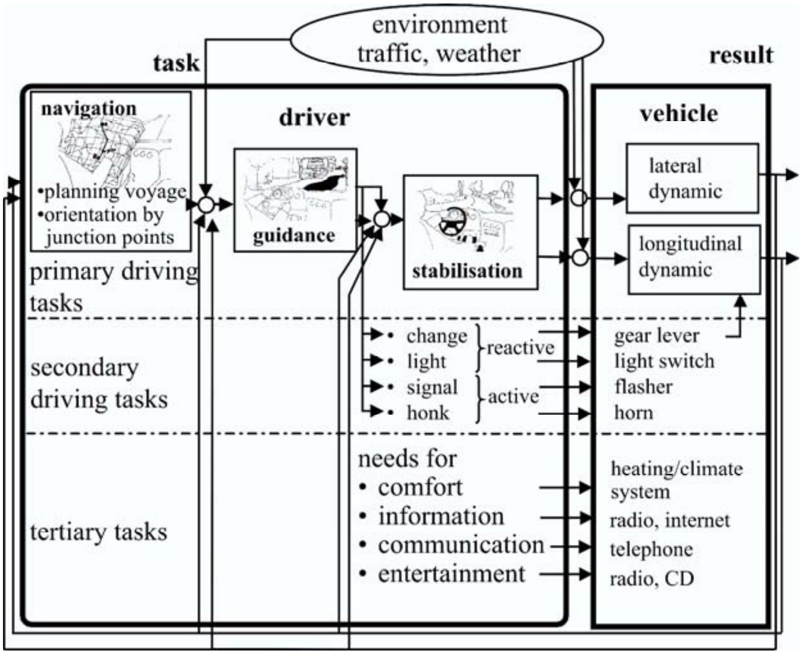


Fig. 2.33 Closed loop driver - car

Driving a car is like controlling any machine and involves steps shown in this closed loop paradigm. The course of the road, vehicles and other traffic participants, as well as environmental and weather conditions determine the driving task. Here the desired lateral and longitudinal position of the car on the road - corresponding to the desired speed – are determined in detail. The task of the driver is to detect the necessary information from the visual environment und to transform it into adequate handling of the control elements. The result is the actual lateral and longitudinal position of the car corresponding fully to the desired position. The driving task can be reduced to the directive “avoid any contact with stationary or moving objects in the traffic field”. The described task corresponds to the “stabilisation task”. To accomplish it the driver has to determine the desired course that fixes how the vehicle will move in location and time in the immediate surrounding field of approximately 200 m. This part of the task is called the “guiding task”. The “navigation task” precedes it. This task lays down in a general way how the existing road network should be connected in order to reach the desired destination. The actual state of the car has to match with all these levels of the task.

The description above does not mention all the tasks that are to be accomplished during driving. According to a proposal of Geiser (1985) the total driving task can be divided in the following subtasks. The primary driving task is the task that has already been described above. It is the actual driving process that aims to keep the car on the road. Besides that the driver has to accomplish additional tasks. These arise in the framework of the primary driving task, depending on traffic and environmental conditions, as well as those necessary to inform other traffic participants about intended manoeuvres. For example the operation of the indicator, the windscreen wiper, the headlamp switch, the horn, and in the case of a manual car the use of gear lever and clutch pedal belong to these tasks. Also assistance systems such as cruise-control or ACC-system have to be operated on this level. Any or all of these control elements have to be used depending directly or indirectly on the driving task. Therefore they are assigned as secondary tasks. They can be divided further into reactive and active tasks. The reactions to a change in external conditions such as dipping the headlights in the case of oncoming traffic or turning on the windscreen wipers in the case of rainfall are reactive tasks. Theoretically they can be automated. With active tasks the driver shows his intention, for example by using the horn. Tertiary tasks are those that have nothing to do with driving, but aim to improve comfort, or provide entertainment and information. They include use of heating and air-conditioning systems, radio and telephone. In the future additional equipment such as internet and for communication with office and home technologies will be available. Here too one can make the distinction between active and reactive tasks.

The investigation and design of the primary task is the area of design that promises a reduction in accident frequency and improved car handling.

But at present current technical developments are allowing much information processing for secondary and especially tertiary tasks. The design of such equipment is the object of current research.

2.3.2 Continuous adjustments of the visual system

Adaptation

The human visual system can be exposed to a very large range of luminances - from 0.000001 cd/m^2 on a very dark night to 100,000 cd/m^2 on a sunlit beach. To cope with this range, the visual system continuously and unconsciously changes its sensitivity through a process called adaptation. Adaptation involves three distinct changes:

Change in Pupil Size - The iris constricts and dilates in response to increased and decreased levels of retinal illumination. For young people the diameter of the pupil can range from about 2 mm to 8 mm. The amount of light transmitted through the pupil is proportional to its area. Therefore this range of diameters implies a maximum effect of pupil changes on retinal irradiance of 16 to 1. As the visual system can operate over a range of about 1,000,000,000,000 to 1, the pupil clearly plays only a minor role in the adaptation of the visual system. Iris constriction is faster (about 0.3 s) than dilation (about 1.5 s).

Neural Adaptation - This is a fast (less than 200 ms) change in sensitivity produced by synaptic interactions in the retina. It is effective over a luminance range of 2-3 log units, which explains why it is possible to look around most lit interiors without being conscious of being maladapted.

Photochemical Adaptation - The four types of retinal photoreceptors contain four different photo-pigments. When light is absorbed by the photoreceptor the pigment is bleached. In the dark the pigment is regenerated and is again available to absorb light. The sensitivity of the eye to light is largely a function of the percentage of unbleached pigment. Under conditions of steady retinal irradiance, the concentration of photo-pigment produced by the competing processes of bleaching and regeneration is in equilibrium. When the retinal irradiance is altered, pigment is bleached and regenerated so as to re-establish equilibrium.

Exactly how long it takes to adapt to a change in retinal illumination depends on the magnitude of the change, the extent to which it involves different photoreceptors and the direction of the change. For changes in retinal illumination of about 2 - 3 log units, neural adaptation is sufficient, so that adaptation should be complete in less than a second. For larger changes photochemical adaptation is necessary. If the change in retinal illumination lies completely within the range of operation of the cone photoreceptors, a few minutes will be sufficient for adaptation to occur. If the change in retinal illumination covers from cone photoreceptor operation to rod photoreceptor operation, tens of minutes may be necessary for adaptation to be completed. As for the direction of change, once the photochemical processes are involved, changes to a higher retinal illuminance can be achieved much more rapidly than changes to a lower retinal illuminance.

When the visual system is not completely adapted to the prevailing retinal illumination, its capabilities are limited. This state of changing adaptation is called transient adaptation. Transient adaptation can be significant where sudden changes from high to low retinal illumination occur, such as on entering a long road tunnel on a sunny day.

Photopic, scotopic and mesopic vision

The process of adaptation can change the spectral sensitivity of the visual system because at different retinal illuminances, different combinations of retinal photoreceptors are operating. The three states of sensitivity are conventionally identified as:

Photopic vision - This state of the visual system occurs at luminances higher than approximately 3 cd/m^2. For these luminances the retinal response is dominated by cone photoreceptors. This means that both colour vision and fine resolution of detail are available.

Scotopic vision - This operating state of the visual system occurs at luminances less than approximately 0.001 cd/m^2. For these luminances only rod photoreceptors respond to stimulation, cone photoreceptors being insufficiently sensitive to respond to the low level of retinal irradiance. This means that colour is not perceived, only shades of grey, and the fovea of the retina is blind.

Mesopic vision - This operating state of the visual system is intermediate between the photopic and scotopic states, i.e. between about 0.001 cd/m^2 and 3 cd/m^2. In the mesopic state both cones and rod photoreceptors are active. As luminance declines through the mesopic region, the fovea, containing only cone photoreceptors, slowly declines in absolute sensitivity without significant change in spectral sensitivity. Eventually vision fails altogether as the scotopic state is reached. In the periphery rod photoreceptors gradually come to dominate cone photoreceptors, resulting in a slow deterioration in colour vision and resolution, and a shift in spectral sensitivity to shorter wavelengths.

The relevance of the different operating states for automotive lighting varies. Scotopic vision is largely irrelevant. Any automotive lighting worthy of the name provides enough light to at least move the visual system into the mesopic state when the driver is looking at the lit area. When road lighting is also present, there may be enough light to ensure that the visual system operates near the boundary of the photopic and mesopic states.

The Commission Internationale de l'Eclairage (CIE) has recognised three different spectral sensitivities known as the CIE Standard Photopic Observer, the CIE Modified Photopic Observer and the CIE Standard Scotopic Observer (Fig. 2.34).

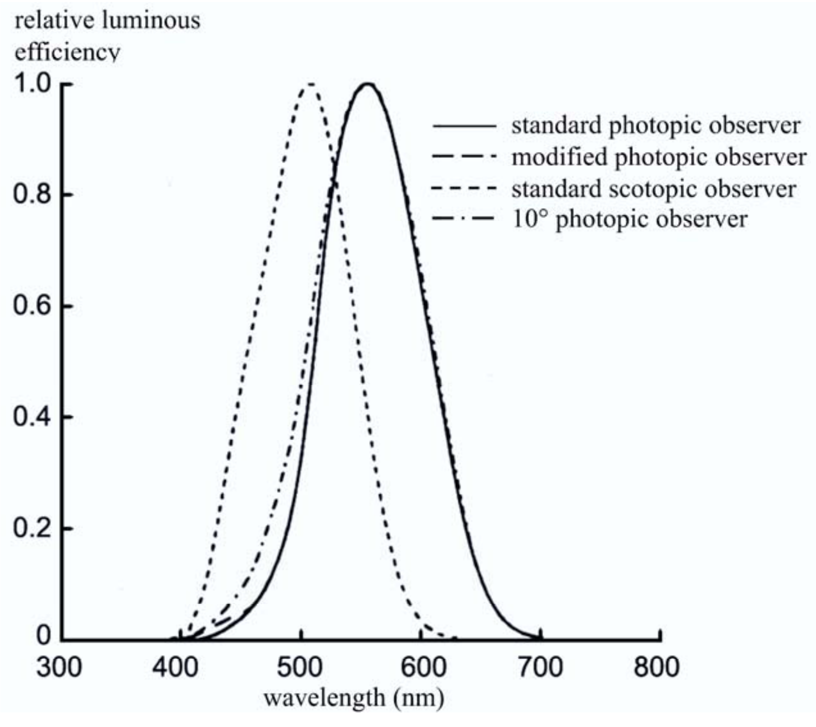


Fig. 2.34 The relative luminous efficiency functions for the CIE Standard Photopic Observer, the CIE Modified Photopic Observer, the CIE Standard Scotopic Observer, and the relative luminous efficiency function for a 10° field of view in photopic conditions.

These relative luminous efficiency functions are used in the fundamental definitions of light to convert from radiometric quantities to photometric quantities. There is no officially recognised spectral sensitivity for the mesopic state, despite extensive study (CIE 1989). But there are models based on both brightness and reaction time, that attempt to describe the transition between photopic and scotopic vision (Sagawa and Takeichi 1986, Rea et al 2004). Virtually all photometric quantities used in lighting practice are measured using the CIE Standard Photopic Observer. Therefore it is not surprising that the visual effects of light sources with different spectral content are not identical when the two light sources are matched photometrically. The fact is that the CIE Standard Observers are primarily designed to facilitate the measurement of light rather than to describe the operation of the visual system precisely.

Eye movements

The emphasis given to the fovea by the visual cortex makes it essential that the visual world is explored by moving the eye so that different parts of the visual world fall on the fovea. There are several different types of eye movement. Searching the visual field is done by a series of fixations and saccades. Fixations are attempts to hold an object of interest steady on the fovea. Movement between fixations is made by saccades. Saccades are very fast, velocities ranging up to 1000 degrees/second depending upon the distance moved. Saccadic eye movements have a latency of about 200 ms, which limits how frequently the line of sight can be moved to approximately five movements per second. Visual functions are substantially limited during saccadic movements.

Almost the only situation in which saccades rarely occur is in smooth pursuit eye-movements. Such movements are relatively slow, up to 40 degrees/second, and are used to keep the image of a smoothly moving object on the fovea. The advantage of such movements is that if successful, the target is always on the fovea, meaning that more detailed information about it can be extracted. The smooth pursuit system cannot follow smoothly-moving targets at high velocities, nor slow and erratically-moving targets.

These eye movements all occur in a single eye, but movements in the two eyes are not independent. Rather they are coordinated so that the lines of sight of the two eyes are both pointed at the same target at the same time. If the lines of sight of the two eyes are not aimed at the same target at the same time, the target may be seen double (diplopia). Movements of the two eyes which keep the primary lines of sight converged on a target, or that switch fixation from a target at one distance to a new target in the same direction but at a different distance, are called vergence movements. These movements are very slow - up to 10 degrees/second, but can occur either as a jump movement, or smoothly following a target moving in a fore-and-aft direction. Both types of movement involve a change in the angle between the two eyes.

Spotlight

Glance and the perceived present

The perceived present has a duration of 2 to 3 seconds and is sometimes called the "present of present" (Poeppel 2000). This present of present has important consequences for our glance behaviour. All experiments with glance behaviour in car driving show that normally information is scanned only a temporal distance of 1 to 1.5 seconds ahead (distance = speed x preview time), (Donges 1978; Yuhara et al 1999; Guan et al 2000; Schweigert 2003).

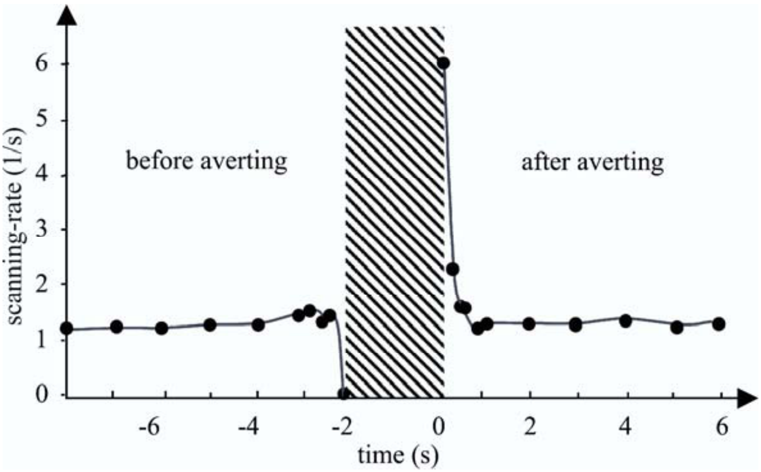


Fig. 2.35 Scanning-rate before and after averting the glance from the road.

Moreover a large body of experimental results show that we normally choose to take the view from the road for up to two seconds (e.g. Zwahlen et al 1988; Gengenbach 1997; Schweigert 2003). Gengenbach (1997) who showed that the scanning rate goes down immediately before the averting, and that after the averting the felt loss on information is compensated for by an increased scanning rate (see Fig. 2.35).

The present of present with a duration of 2 to 3 seconds encourages us not to keep our glance always on the road. Schweigert (2003) carried out glance research in enlarged experiments. He found that the glance was also directed to non-traffic-relevant objects in 89% of all observed traffic situations under normal non-stressing conditions. When the traffic situation becomes more difficult, we first reduce glances on non-traffic-relevant objects, then on specific areas of interest, then on traffic signs, tachometer and mirrors. When the situation becomes very complex, it can be observed that in 41% of all cases the driver relies on other traffic participants behaving according to the rules.

When the situation becomes still more complex, in 7% of situations the driver omits even the glance to primary necessary information (see Fig. 2.36). Thus the free glance not bound by the traffic situation can be seen as an indicator for the mental load under these conditions. Schweigert conducted comparable experiments with additional oral and visual tasks that used the aspect of attraction of attention. Here one observes a further reduction of free glances with these additional tasks. In the figure above the change in relation to the situation with no interference is indicated. It can be observed that an additional oral task has on average a little less influence than an additional visual task.

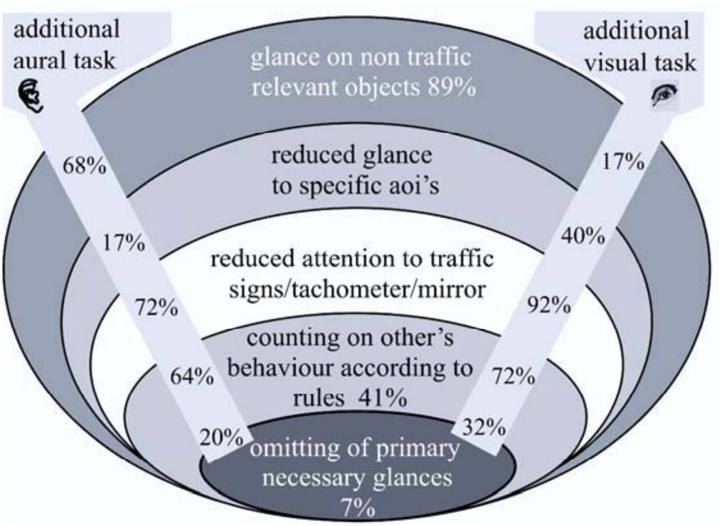


Fig. 2.36 Percentage of faulty glance behaviour (Schweigert 2003)

In a further investigation on glance behaviour by Rassl (2005), the influence of tertiary task and different layout of such tasks was observed in greater detail. Amongst other choices his subjects had to choose one of 3, 5, 8, and 14 options using a central control element (similar to the BMW i-drive controller) during driving. It is of interest that the selection takes on average about 1.2 seconds, and there is no significant difference between these deviation times depending on the number of presented options. However, when we look at the maximum duration of distracted glances, the case with 14 options is significantly different from the others. The maximum distraction time in this case is on average 2.2 seconds. As the figure above shows, in one case a distraction time of as much as 12 seconds was observed. This is not unusual!

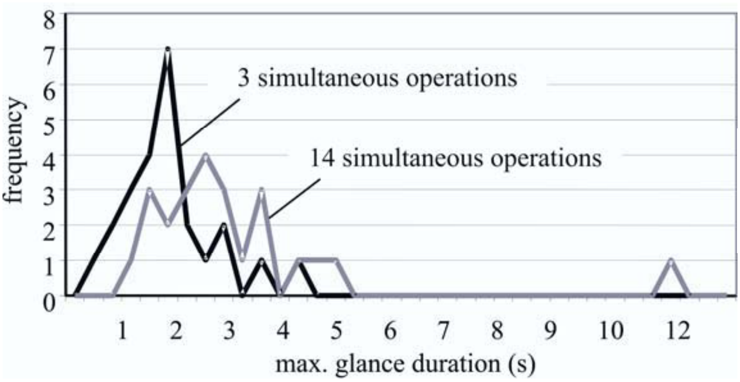


Fig. 2.37 Glance attention in connection with tertiary tasks

In another part of Rassl's experimental research a distraction time of as much as 16 seconds was observed. In further unpublished experiments on the operation of the ACC-system we also found distraction times of 12 seconds. The psychological explanation for these long dark periods is given by the present experience. Normally after two seconds of distraction we become worried and turn our glance back to the road. However, in rare cases we use the total time span between present of past and present of future. For example if at the start of the distraction we had the impression of a scene promising no big changes, and if additionally the distracting task becomes attractive. We do not recognise subjectively the long distraction time from the road in any of these cases, because our internal model is showing us the supposed scene on the road.

Spotlight

Glance behaviour during driving

In general glance behaviour is one indicator showing how visual information is acquired by the visual system of the brain. The fovea of the eye subtends only a small solid angle of about 2 to 3 degrees in which visual features can be resolved sharply. The eye must scan the scene sequentially in order to apprehend the situation. Thus the strategy of this scanning behaviour depends on the attractiveness of the objects in the environment (see Fig. 2.38). Glance behaviour can be seen as a periscope into the internal information processing behaviour.

However in the peripheral sphere of the eyes the receptor cells are connected even at the level of complex and hyper-complex neuron cells, in such a way that this sphere is especially sensitive for stimulation by moving light reflections. These cells are directly connected with the eye muscles via specific brain areas – the Chiasma, Colliculi Superiores and Formatio Reticularis. This means that any changing stimulus that reaches the peripheral sphere of the eyes immediately redirects the glance at the moving object. Only by concerted effort can we resist this impulse.

It is important to remember therefore that glance direction is only an indicator for attention. It is necessary to distinguish between intentional "turning away" and involuntary "distraction".

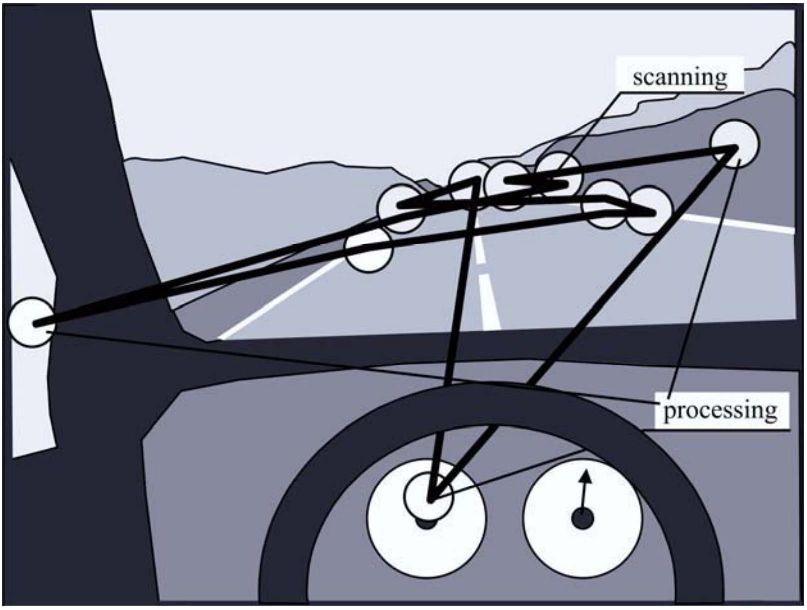


Fig. 2.38 Glance behaviour during driving.

When observing glance behaviour using an eye tracking system (e.g. DIKABILIS) during driving, we can distinguish between "scanning" and "processing". Scanning glances have a rather short duration - on average 400 ms. Scanning in particular the edges of the road allows perception of other traffic participants and traffic signs. Processing means that special so-called areas of interest (AO's) are fixated. These can be instruments, the mirror and the navigation display of the car, but also objects in the environment that are not relevant to traffic. Processing glances are on average twice as long as scanning glances (see Fig. 2.39).

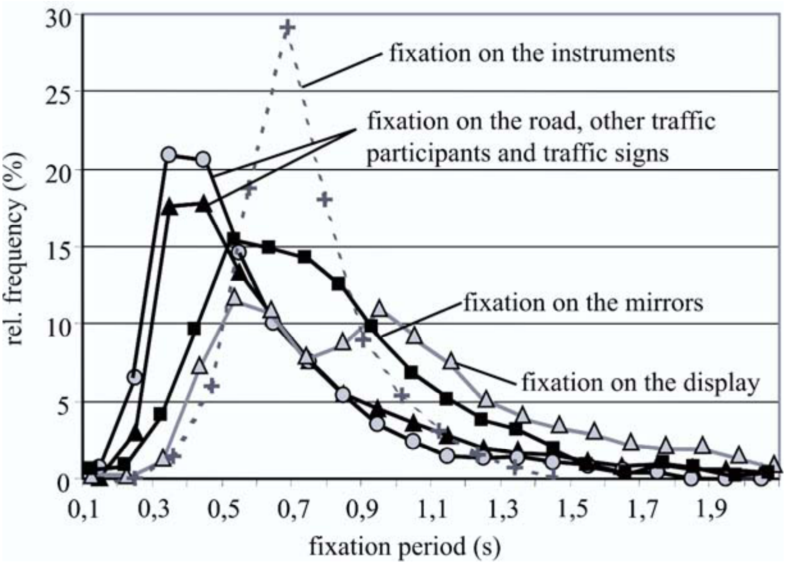


Fig. 2.39 Experimental results of eye tracing research (Schweigert 2003)

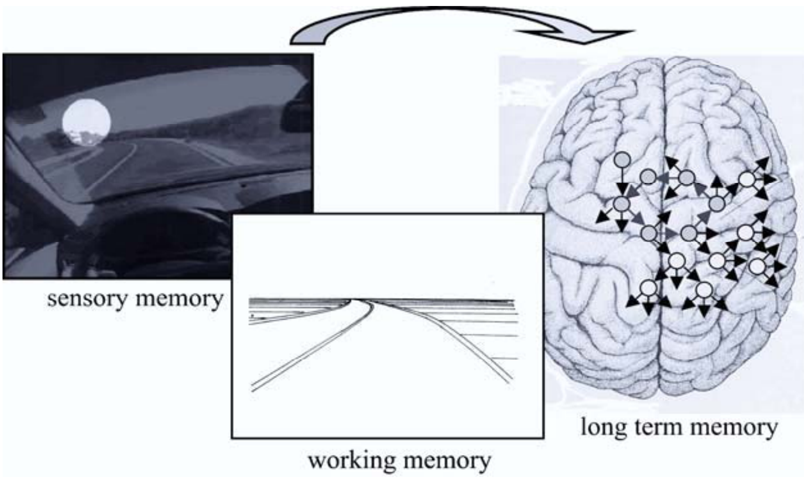


Fig. 2.40 Stimulation of internal models by external stimuli.

How can we infer an image from information captured by these results? The figure above helps us to understand this process. By scanning on the level of the sensory memory, information is taken in to stimulate internal models in our long term memory. These are stored as a general concept in form of a structural engram. This stimulation awakens the corresponding internal model and thus becomes a part of the working memory. We can understand this process more precisely by looking at the example of driving on a road bending to the left. The information received by scanning stimulates a general internal model of a concept of a road bending to the left. By adapting this concept to the real stimuli in the working memory, we recognise the real width and the real curve of this particular road. Further scanning stimuli give us information about traffic participants on this road. The scanned information of these objects also stimulates internal models of their behaviour. In this way even a short glance is enough to comprehend the speed and the course of an oncoming car or the expected behaviour of a pedestrian. As our glance can only scan the scene sequentially, it is possible that relevant objects are missed. The combination of all this information causes us to believe the presence of a certain objectivity.

Spotlight

Conspicuity: Visible and different

Eye movements during driving consist of a series of fixations, with rapid jump movements called saccades between fixations. Each fixation allows resolution of detail in a small area around the fixation point, and detection of any changes occurring over a much wider area. Vision is suppressed during the saccade movement. The maximum number of fixations per second is about five, so there is inevitably a large part of the road ahead that is never examined in detail by the driver. This means that an event such as the application of brake lights in a vehicle ahead, or an obstacle on the edge of the road such as a pedestrian, is most likely to be detected initially off-axis. The probability of off-axis detection is greatly increased if the event or object is not only visible but also conspicuous.

Visibility and conspicuity

The characteristics of an object determining its visibility are size, contrast and colour difference between the objects and its background. Visibility of the object increases with size, contrast and colour contrast between the object and its background. Fig. 2.41 shows a very simple example. The single black disc on white paper is more visible than the single light grey disc. Visibility is a necessary condition for off-axis detection, but it is not a sufficient condition to make the object conspicuous. To make an object conspicuous it has to have some feature that easily differentiates it from other objects around it. Again, in Fig. 2.41 the black discs in the array are all highly visible, but none of them is conspicuous relative to the others. However, changing the markings of the central disc makes it conspicuous as well as visible.

Although changing the markings has been used to provide conspicuity in this example, it is important to appreciate that there are many other features that can be used to produce conspicuity, e.g. colour, size, shape, luminance, flicker, movement. Which of these is most effective will depend on the specific circumstances. The choice of the feature or features used should be made on the basis of the visibility of the feature and its rarity. For example there is little point in using colour to enhance conspicuity if the colour is similar to the background colour so that it is not highly visible, or when all the other objects have a wide variety of colours. To be conspicuous it is necessary to be both visible and different.

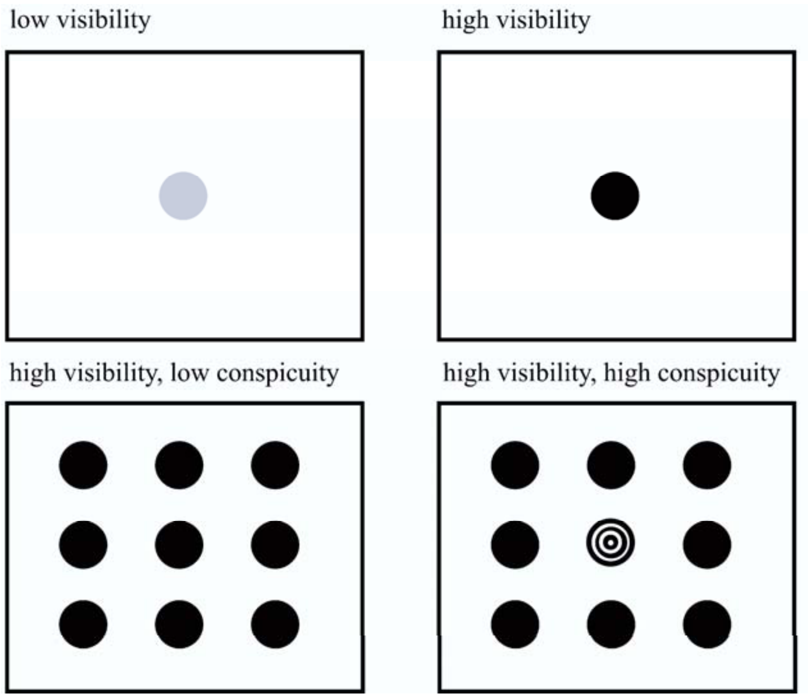


Fig. 2.41 Increasing luminance contrast enhances visibility, but a visible difference is required to be conspicuous.

Practical examples

Three examples of automotive lighting being used to enhance conspicuity are:

Motorcyclists are encouraged to ride with their headlights on during the day. The idea here is that by doing so the motorcycle will stand out from other vehicles, and the number of motorcyclists injured by other vehicles crossing their path will be reduced. Unfortunately the growth in the use of daytime running lights on automobiles has reduced the conspicuity benefit for the motorcyclist when in traffic, because there are many vehicles moving with lights on. They will all be more visible but none will be conspicuous. Indeed it could be argued that once the number of vehicles with daytime running lights exceeds a certain proportion, those vehicles without daytime running lights will be at a disadvantage because they will be inconspicuous.

Emergency vehicles are fitted with flashing lights visible from all directions to indicate their status and the urgency of their mission. The combination of colour for information and a high luminous intensity, high modulation, a repetitive, flashing signal to attract attention, together with the prohibition of such signals on other vehicles, is enough to ensure conspicuity.

All cars are fitted with hazard warning systems to make all four indicators flash repetitively when the vehicle is disabled either in traffic or close to traffic. It is the fact that all the indicators can be seen flashing in phase that makes this signal conspicuous.

Accommodation

The eye has a fixed image length. In order to focus different objects at different distances onto the retina requires changes in refractive power. There are three optical components involved in the ability of the eye to focus an image on the retina. The first is the thin film of tears on the cornea. This film is important because it cleans the surface of the eye, starts the optical refraction process necessary for focusing objects, and smoothes out small imperfections in the surface of the cornea, the second optical component. The cornea covers the transparent anterior one-fifth of the eyeball (Fig. 2.28). Together with the tear layer, it forms the major refracting component of the eye and gives the eye about 70% of its refractive power. The crystalline lens provides most of the remaining 30% of the refracting power. The ciliary muscles have the ability to change the curvature of the lens and thereby adjust the power of the eye's optical system in response to changing target distances; this change in optical power is called accommodation. Accommodation is a continuous process and is always a response to an image of the target located on or near the fovea rather than in the periphery of the retina. As adaptation luminance decreases below 0.03 cd/m^2, the range of accommodation narrows, so that it becomes increasing difficult to focus objects near and far from the observer (Leibowitz 1975). Blurred vision and eye strain can be consequences of limited accommodative ability. When there is no stimulus for accommodation, e.g. in complete darkness, or in a uniform luminance visual field such as occurs in dense fog, the visual system typically accommodates to approximately 70 cm away.

2.3.3 Visual capabilities

The human visual system has a limited range of capabilities. A convenient way to describe these limits is to set out what are called the thresholds of vision. Threshold measurements come in many different forms and depend on many different variables, most of which interact. They provide well-defined and sensitive metrics to explore the operation of the visual system under different conditions. For lighting practice, threshold measurements are mainly of interest for determining what will not be seen, rather than how well something will be seen. The intention here is to summarise the thresholds of relevance to driving at night. For these threshold measurements it can be assumed that the observers are all adapted, that the target is presented on a field of uniform luminance and that the observers' accommodation is correct.

Threshold measures

The threshold capabilities of the human visual system can conveniently be divided into spatial, temporal and colour classes.

Spatial threshold measures: Spatial threshold measures relate to the ability to detect a target from its background or to resolve detail within a target. For spatial threshold measures, it is usually assumed that the target does not vary with time. Common spatial threshold measures are threshold luminance contrast and visual acuity.

Temporal threshold measures: Temporal threshold measures relate to the speed of the response of the human visual system and its ability to detect fluctuations in luminance. For temporal threshold measures it is usually assumed that the target is fixed in position.

Colour threshold measures: Colour threshold measures are based on the separation in colour space of two colours that can just be discriminated. The separation is most commonly measured on the CIE 1931 (x,y) Chromaticity Diagram and the related Uniform Chromaticity Scale diagrams.

Factors determining visual threshold

There are three distinct groups of factors that influence the measured threshold, using any of the above metrics. These groups are visual system factors, target characteristics and the background against which the target appears.

Important visual system factors are the luminance to which the relevant part of the retina is adapted, the position in the visual field where the target appears, and the extent to which the eye is correctly accommodated. The luminance to which the retina is adapted determines which photoreceptor types are operating. The position in the visual field in which the target appears determines the type of photoreceptors available. The state of accommodation determines the retinal image quality. For driving, it is reasonable to assume that accommodation will be correct, but both the luminance to which the relevant part of the retina is adapted and the position of the target on the retina can vary widely.

Important target characteristics are the size and luminance contrast of the target and the colour difference between the target and the immediate background. Any one of these three task characteristics can be the threshold measure of interest but the others will interact with it. This means that the threshold contrast of a target will be different for targets of different size, with or without a colour difference. For driving, target characteristics can vary greatly. Size changes as the driver approaches an obstacle and the luminance of a pedestrian will depend on the reflectance of the clothing being worn.

As for the effect of the background against which the target appears, the important factors are the area, luminance and colour of the background. These factors are important because they determine the adaptation state of the part of the retina on which the image of the target falls and the luminance contrast and colour difference of the target. For driving, the luminance and colour of the background can again vary widely depending on the light distribution from the headlights and the presence or absence of road lighting.

Spotlight

Road lighting and headlights

Interaction

The presence of road lighting modifies the effectiveness of headlights in two ways. Firstly it can change the visibility of objects on the road. Secondly it can alleviate the effects of glare from opposing headlights.

Visibility

Both road lighting and headlights are designed to make what is ahead visible to the driver. Road lighting does this by lighting the road so that objects on the road are seen in silhouette against the road surface. Headlights make things visible by preferentially lighting the vertical surfaces of objects on the road rather than the horizontal road surface. For objects to be visible a luminance contrast above threshold is necessary. Exactly what that threshold contrast is will depend on the size of the object. Therefore the visibility of an object on the road will depend on the relative luminances of the object and the road surface against which it is seen, and on the distance from the observer.

Variations in the road surface luminance produced by road lighting mean that the visibility of an object varies along the road.

Magnitude of effect

Bacelar (2004) has reported a series of measurements of object visibility under road lighting with and without dipped and main beam headlights. Visibility was quantified as Visibility Level, this being the ratio of actual luminance contrast to threshold luminance contrast, calculated using the model of Adrian (1989). The object was placed at a constant distance of 40 m from the vehicle for dipped headlights, and 90 m for main beam headlights. The object was a vertical, diffusely-reflecting, 0.2 m square plate of reflectance 0.2. The object was moved in 5 m steps along the road between two of the columns used for road lighting, successive columns being separated by 30 m. The road lighting produced an average road surface luminance of 2.45 cd/m^2, an overall luminance uniformity of 0.6 and a longitudinal luminance uniformity of 0.7. Fig. 2.42 shows the variation in visibility level for road lighting alone, headlights alone and road lighting and headlights together. It is clear that for the dipped headlights, when the object is between 5 m and 20 m from the column, road lighting and headlights together produce lower Visibility Levels than either system alone. For the main beam headlights the road lighting and the headlights together produce lower Visibility Levels than either system alone, at all positions.

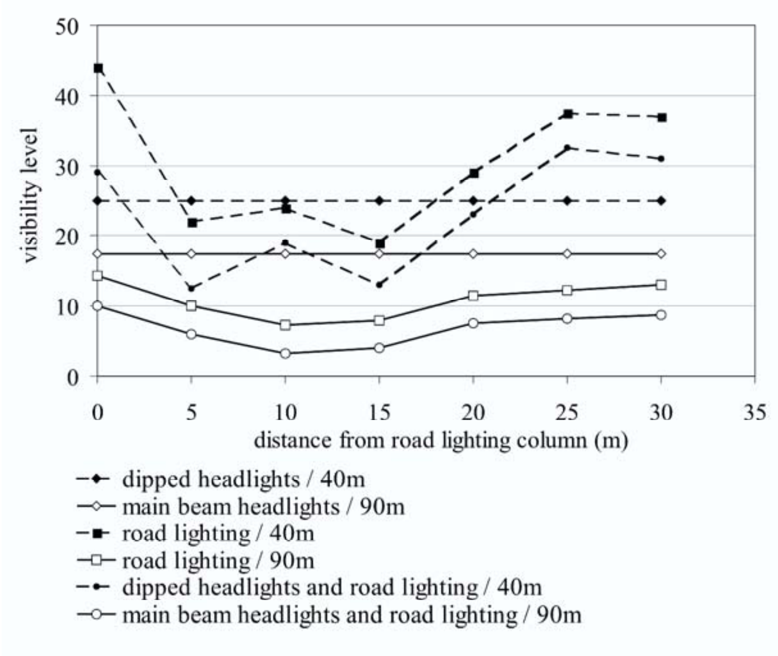


Fig. 2.42 Visibility Levels calculated from luminance measurements taken for a vertical target of reflectance 0.2 at a distance from the driver of 40 m for dipped headlights, and 90 m for main beam headlights, plotted against the position of the target relative to a road lighting column. Successive columns of the road lighting are separated by 30 m. Measurements were taken for headlights alone, road lighting alone and headlights and road lighting together (after Bacelar 2004)

Disability glare

Another interaction of road lighting and automotive lighting involves the change in the effects of the disability glare caused by the headlights of opposing vehicles. Disability glare, as its name implies, produces a measurable change in visibility because light scattered in the eye reduces the luminance contrasts in the retinal image. Bacelar (2004) also reported changes in Visibility Level for the target positioned 40 m ahead, with and without road lighting, and in the presence of one or three opposing vehicles using dipped headlights. Fig. 2.43 shows the calculated Visibility Levels, for different distances between vehicles, with and without road lighting. It is clear that at 40 m, providing road lighting increases Visibility Levels above those possible with dipped headlights alone, that introducing glare reduces Visibility Levels, that three opposing vehicles produce greater reductions in Visibility Levels than one opposing vehicle and that the reduction in Visibility Level caused by disability glare from opposing vehicles is less when road lighting is present.

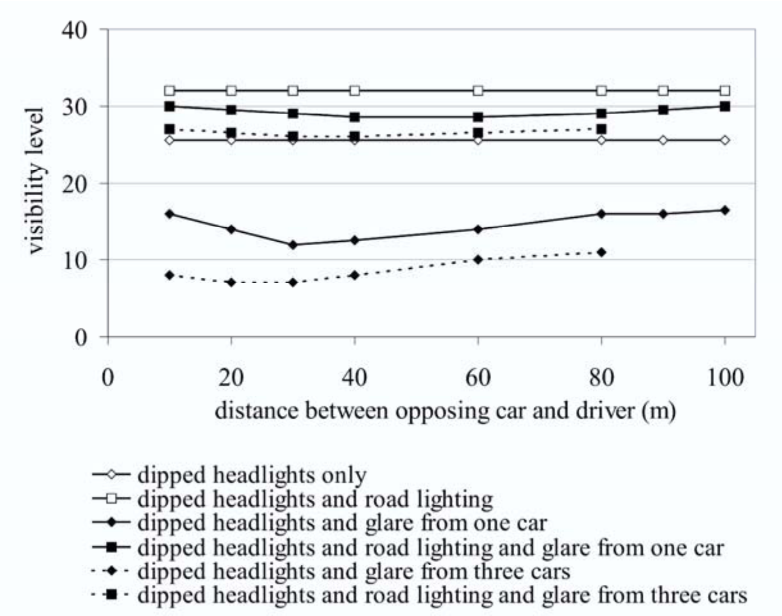


Fig. 2.43 Visibility Levels calculated from luminance measurements taken for a vertical target of reflectance 0.2 at a distance from the driver of 40 m for dipped headlights, without disability glare and with disability glare from one or three opposing cars, plotted against the distance between the opposing car and the driver (after Bacelar 2004)

Reality

It is important to appreciate that these visibility level results represent an extreme version of reality. Objects on the road rarely consist of a single surface of one reflectance on a single plane. Often they are composed of surfaces on different planes and the reflectances of the surfaces differ in both kind and degree, i.e. they can be both diffusely and specularly reflecting to different extents. Further, because these surfaces are in different orientations to the lighting, the illumination falling on each surface will be different. All this means that many objects found on roads will have a wide range of luminances and hence will have multiple luminance contrasts and multiple visibility levels. This means that in reality, it is unlikely that all parts of an object will cease to be visible at the same instant. It is much more likely that the changes in visibility of different parts of the object will cause a change in appearance. Such changes in appearance may cause problems with identification but are not likely to affect adversely detection of the object. Nonetheless, the possibility that there are some objects for which the changes in visibility shown above are realistic, should be sufficient to justify modifying the light distribution from headlights in the presence of road lighting to maintain visibility.

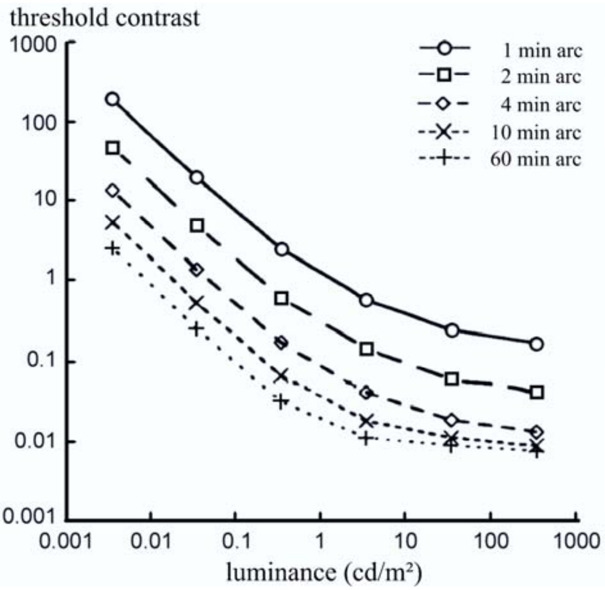


Fig. 2.44 Threshold contrast plotted against background luminance for disc targets of various diameters, viewed foveally. The discs were presented for 1 second (after Blackwell 1959)

Spatial thresholds

About the simplest possible visual task is the detection of a spot of light presented continuously against a uniform luminance background. For such a target the visual system demonstrates spatial summation, i.e. the product of target luminance and target area is a constant. This relationship between target luminance and target area is known as Ricco's Law. It implies that the total amount of energy required to stimulate the visual system so that the target can be detected is the same, regardless of whether it is concentrated in a small spot or distributed over a larger area. Spatial summation breaks down when the target is above a given size, called the critical size. The critical size varies with the angular deviation from the fovea. It is about 0.5 degree at 5 degrees from the fovea, and about 2 degrees at 35 degrees from the fovea (Hallett 1963). There is very little spatial summation in the fovea, the critical size being about 6 min arc.

Given that the size of the target is above the critical size, the effect of background luminance on threshold contrast for targets of different size is shown in Fig. 2.44. The increase in threshold contrast as background luminance decreases is obvious, as is the increase in threshold contrast with decreasing target size (Blackwell 1959). These data were obtained using a disc of different sizes presented for 1 second. Decreasing the presentation time increases the threshold contrast for all sizes, particularly at lower adaptation luminances.

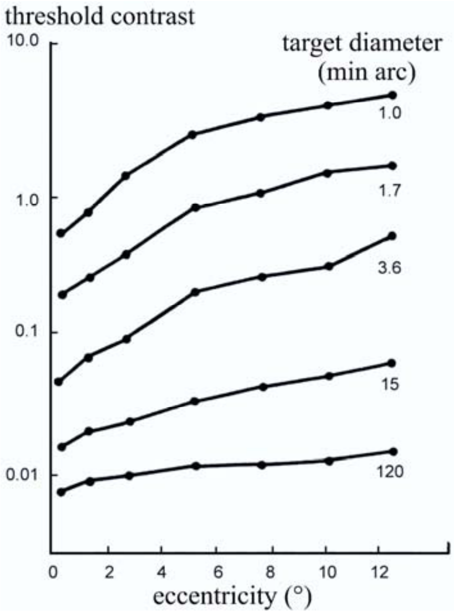


Fig. 2.45 Threshold contrast for disc targets of various diameters, presented for 330 ms, at various degrees of eccentricity, at a background luminance of 257 cd/m^2 (after Blackwell and Moldauer 1958)

Fig. 2.45 shows threshold contrast measured for circular targets of different sizes, occurring at different eccentricities from the fovea (Blackwell and Moldauer 1958). It can be seen that the threshold contrast is a minimum at the fovea and increases as eccentricity from the fovea increases.

Also apparent is the interaction between the size of the disc and the eccentricity of its locations. Specifically, higher threshold contrasts are associated with smaller target sizes, and the increase in threshold contrast with increasing eccentricity is greater the smaller the size of the disc.

Threshold contrast is relevant to the detection of targets on a background. Targets with a luminance contrast close to or below the threshold value are unlikely to be seen, whereas targets with a luminance contrast more than twice the threshold value are likely to be seen every time, provided the conditions are similar to those in which the threshold measurements were made.

Spotlight

Contour lighting

In daylight objects acquire shadows and highlights. Both are a welcome addition as they enhance contrast and mark the contours of objects thus making it easier for our visual system to pick them up.

Fig. 2.46 Day-time driving scene and areas of high contrast

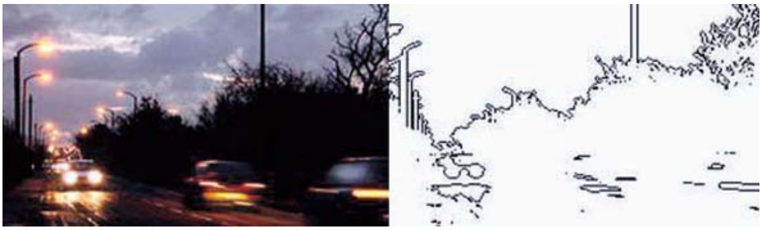


Fig. 2.47 Night-time driving scene and areas of high contrast

In darkness the contours tend to disappear because of the scattered shadows and highlights, as well as adaptation thresholds. As a result objects are more difficult to pick up and identify. This applies to traffic, where cars at night may no longer appear as one unit but are seen as distinct spots.

With a little effort contours can be made visible at night. The following examples illustrate the possibility.

Fig. 2.48 Passive contour marking using reflective foil (source: 3M)

Passive contour lighting application

A very simple but effective way of marking contours is by use of reflective material. Reflective foil is used in clothing to mark people who have to work on roads at night. Contours of trucks can be marked using white or coloured reflective material. This greatly increases conspicuousness and makes it easier for other drivers to estimate size, speed and direction of the truck.

Fig. 2.49 Under floor lighting (right) accentuates the contour of the vehicle

Under floor lighting

The contrast provided by the shadow in daylight can be created using under floor lighting. Even though the contrast is inverted the contour of the car is recognised as if there was a shadow.

Contoured signal lights

In foggy conditions the contrast is greatly reduced. Tail lights become faint or disappear from view. The higher intensity fog light may help visibility. A light which follows the vehicle contour is more easily discerned.

Benefits of contour lighting

There are many forms of contour lighting. The all tend to make it more intuitive for an observer to recognize the object. In traffic contour lighting aids spatial orientation and the judgment of speed and direction. The chances for a critical manoeuvre or signal being overlooked become considerably smaller if the contour of vehicles becomes visible, and signal lights are long enough to almost span the width of the vehicle.

Fig. 2.50 Contoured signal lights are easier to pick up in low contrast conditions

It should be noted here that current research (Spitzer 2004) indicates that the human vision system has contour recognition built in at a very early stage in the complex network of the visual cortex. Using tomography to watch the processing of stimuli there is evidence that we recognise typical contours in about 100 ms, whereas we can identify colour only after about 400 ms.

Threshold contrast is relevant to the detection of a complete target e.g. a pedestrian at the edge of the road. Visual acuity is relevant to seeing detail within a target e.g. reading a direction sign. Fig. 2.51 shows the variation in visual acuity with adaptation luminance for foveal viewing of the target. As adaptation luminance increases, visual acuity, measured as the reciprocal of the minimum detectable gap size, increases, approaching an asymptote at very high luminances corresponding to about 0.45 min arc (Shlaer 1937).

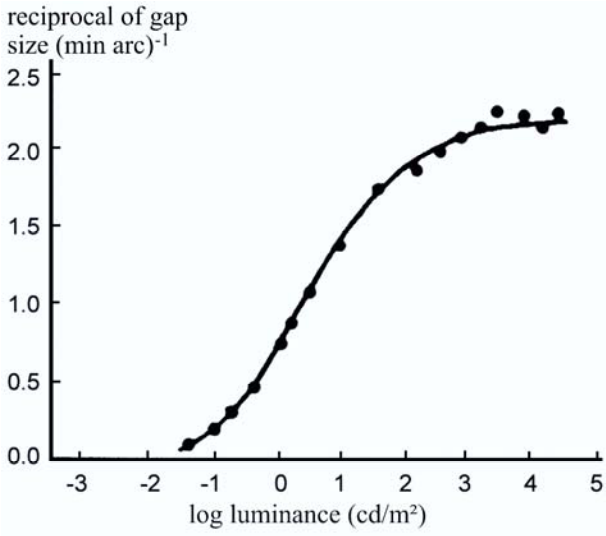


Fig. 2.51 Visual acuity expressed as the reciprocal of the minimum gap size, for a Landolt ring, plotted against log background luminance (after Shlaer 1937)

Fig. 2.52 shows visual acuity, measured as the reciprocal of the minimum detectable gap size, plotted against eccentricity, for a range of adaptation luminances. For the adaptation luminance of 3.2 cd/m^2 i.e. for photopic conditions, acuity is at about 1 min arc in the fovea and declines rapidly to about 10 min arc as eccentricity increases. For adaptation luminances below 0.006 cd/m^2, i.e. in the scotopic state where the fovea is blind and only the rod photoreceptors are active, visual acuity is best at about 10 min arc, 4 to 8 degrees off- axis (Mandlebaum and Sloan 1947).

So far threshold contrast and visual acuity have been considered separately. This is because threshold contrast is usually measured with large size targets without detail, and visual acuity is measured with high luminance contrast targets with detail. But many objects of interest to the driver are likely to vary in both contrast and size of detail and these two target characteristics can be expected to interact. The threshold capabilities of the visual system to such targets can be expressed as the contrast sensitivity function. This is a rather grand name for what is essentially a simple piece of information- the frequency response of the visual system to spatial variations in luminance. Fig. 2.53 shows contrast sensitivity functions for different adaptation luminances (Van Nes and Bouman 1967).

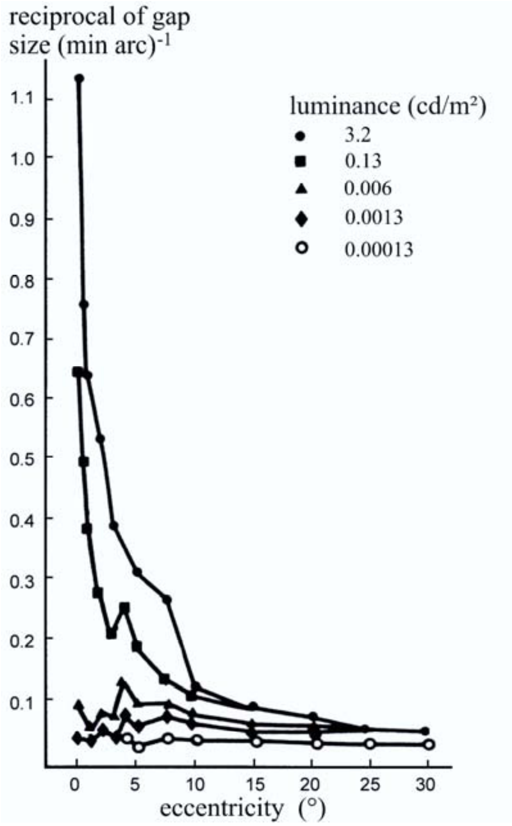


Fig. 2.52 Visual acuity expressed as the reciprocal of minimum gap size, for a Landolt ring target presented at different degrees of eccentricity, over a range of background luminances covering the photopic, mesopic and scotopic states of the visual system. (after Mandelbaum and Sloan 1947)

The value of this apparently esoteric piece of information is that any variation in luminance across a surface can be represented as a wave form, and any waveform can be represented as a series of sine waves of different amplitudes and frequencies. The response of the visual system to sine waves of different amplitudes and frequencies is given by the contrast sensitivity function. Thus the contrast sensitivity function can be used to determine if a complex variation in luminance will be seen. If the luminance pattern has contrast sensitivities at all spatial frequencies that are greater than the matching threshold contrast sensitivities, the luminance pattern will be invisible. It is only when at least one spatial frequency has a contrast sensitivity below the threshold contrast sensitivity that the luminance pattern will be visible. The extent to which the luminance pattern will be seen in its entirety depends on the number of spatial frequencies for which the contrast sensitivity lies below the threshold contrast sensitivity. The more spatial frequencies for which this occurs, the more complete is the perception of the luminance pattern.

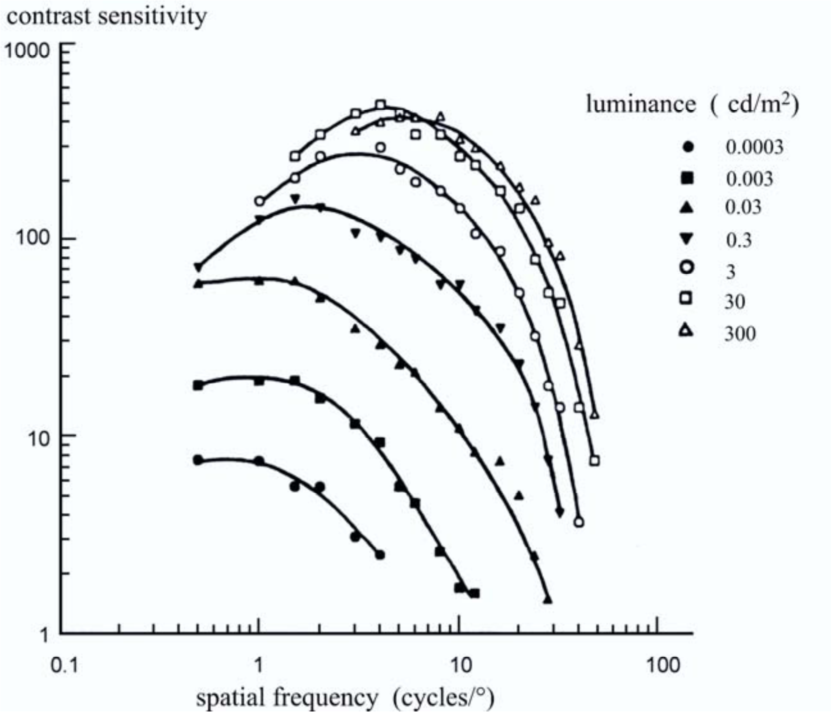


Fig. 2.53 Contrast sensitivity functions for sine-wave gratings at different levels of background luminance, covering the photopic, mesopic and scotopic states of the visual system (after van Nes and Bouman 1967)

Contrast sensitivity functions can be used for many practical purposes. For example they can be used to determine what size a road sign needs to be to be read from a given distance. The distance from which the observer views the luminance pattern is important, because changing the viewing distance changes the spatial frequency of the pattern. As viewing distance increases, the spatial frequency of a fixed grating increases.

From Fig. 2.53 it is apparent that decreasing adaptation luminance decreases both contrast sensitivity and the maximum spatial frequency detectable i.e. it produces a higher threshold contrast and poorer visual acuity. Also clear is that the change in contrast sensitivity function is slight for high luminances, but it changes rapidly below an adaptation luminance of about 30 cd/m^2. The deterioration takes the form of reduced contrast sensitivities at all spatial frequencies and a shift in the spatial frequency at which maximum contrast sensitivity occurs to lower values.

The effect of eccentricity on the contrast sensitivity function is shown in Fig. 2.54. As might be expected from the increase in receptive field size, with increasing eccentricity the contrast sensitivity function shows a dramatic reduction in the highest spatial frequency visible, as deviation from the fovea increases, as well as a reduction in peak contrast sensitivity. This means that it is not possible to see fine detail more than a few degrees away from the fovea.

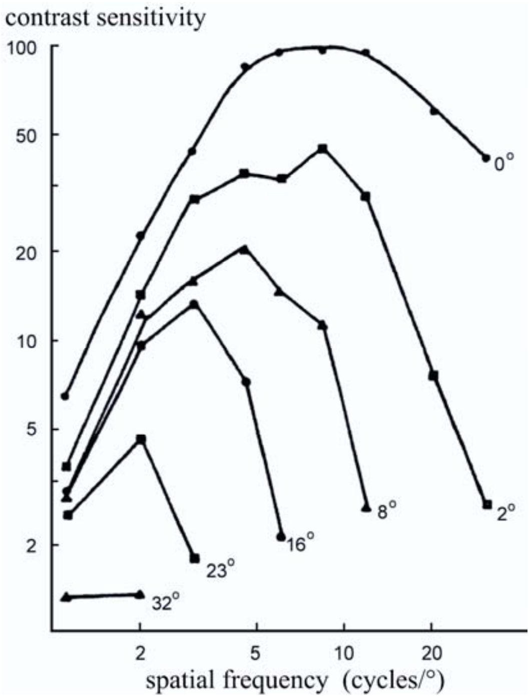


Fig. 2.54 Contrast sensitivity functions for a 2.5 degree stimulus presented at different degrees of eccentricity (after Hilz and Cavonius 1974)

Temporal thresholds

The simplest possible form of temporal visual task is the detection of a spot of light briefly presented against a uniform luminance background i.e. a flash of light. For such a target the visual system demonstrates temporal summation i.e. the product of target luminance and the duration of the flash is a constant. This relationship between target luminance and duration is known as Bloch's Law. It implies that the total amount of energy required to stimulate the visual system in such a way that the target can be detected is the same, regardless of the time for which the target is presented. Temporal summation breaks down above a fixed duration, called the critical duration. The critical duration varies with adaptation luminance, ranging from 0.1 s for scotopic luminances to 0.03 s for photopic luminances. For presentation times longer than the critical duration, the ability to detect the flash is determined by the difference in luminance between the flash and the background alone.

While the ability to detect a single flash is of interest for signalling purposes, another aspect of temporal thresholds of relevance to automotive lighting is the ability to detect a repetitive flash. Fig. 2.55 shows a simple way of determining if a repetitive flash will be seen to flicker. Fig. 2.55 shows the threshold modulation of a sine wave fluctuation plotted against the frequency, for a 4 degree target of average luminance equal to 100 cd/m^2, seen against a dark surround (Kelly 1959). It is evident that the visual system is most sensitive in the frequency range 10 to 20 Hz as this is where the threshold modulation is lowest.

Fig. 2.55 can be used to determine if a signal light fluctuation will be seen to flicker, by determining the actual modulation at all frequencies. For a sine wave oscillation, if the modulation at the given frequency is below the curve, the flicker will not be visible. If it is above the curve, it will be visible. But what can be done if the waveform is not sinusoidal? To predict whether such a waveform will be seen to flicker, the waveform should be represented by a Fourier series of different frequencies and modulations. If the modulations of all the components of the series lie below the curve, then the fluctuation will not be seen to flicker. If any of the components are above the curve, the fluctuation will be seen to fluctuate in some way. Of course the curve in Fig. 2.55 can be expected to shift if the average luminance of the target is raised or lowered. Increasing the average luminance will increase sensitivity i.e. lower the curve, and lowering the average luminance will decrease sensitivity i.e. raise the curve.

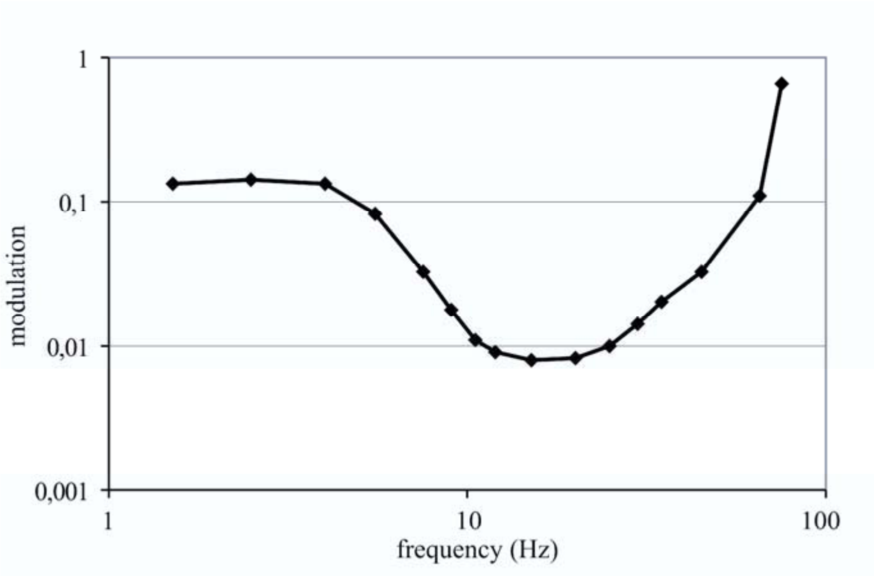


Fig. 2.55 Threshold modulation for a sine wave fluctuation plotted against frequency. The target subtended 4 degrees at the eye, had an average luminance of 100 cd/m^2, and a dark surround (after Kelly 1959)

Spotlight

Braking is hard to do

Tests in daylight and at night time show that the first phase of the reaction process in a hazardous situation – the psychophysical reaction – comprises the largest share of the reaction time. In addition there are different demands made on reaction in the dark. Thus for example, a bright stop light in the dark causes a much greater psychophysical reaction, because it is much more conspicuous and has a higher luminance contrast than a pedestrian wearing dark clothes.

Numerous objects change the line of vision and produce demands to react. In order to understand better the relatively long time that elapses before a reaction occurs, the different eye movements and changes in the line of vision must first be explained in more detail. The following steps occur:

- peripheral perception – most objects are perceived peripherally at first
- saccades which change the line of vision – necessary to be able to picture the object foveally
- identification of the object
- decision

- reaction – stopping, steering

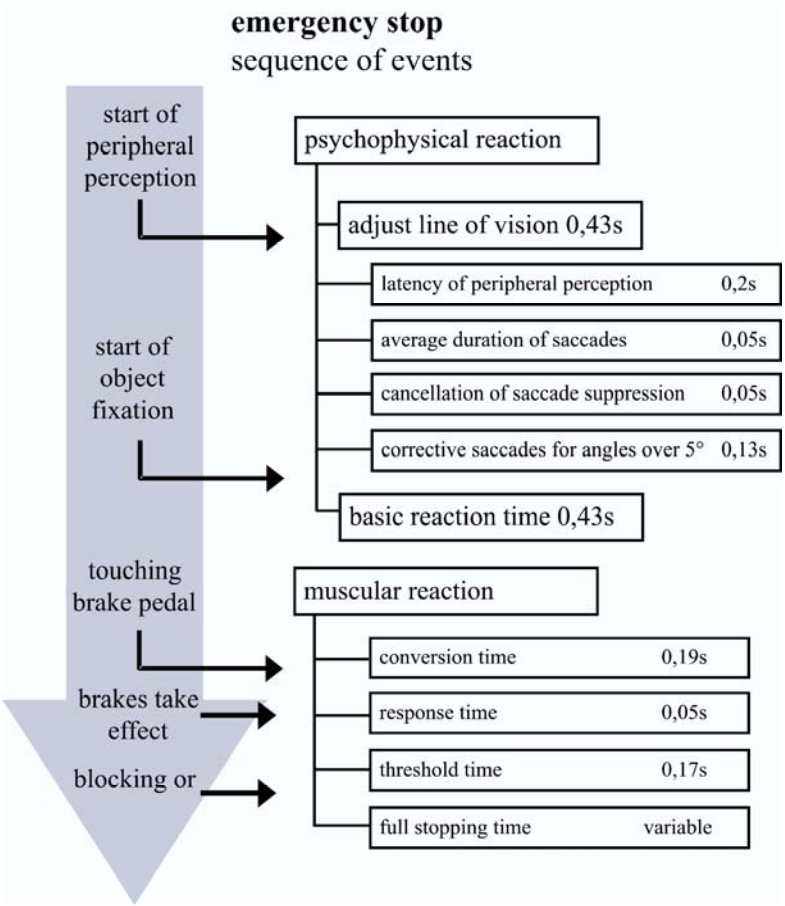


Fig. 2.56 Typical sequence of events for an emergency stop

The temporal sequence of events of emergency stopping happens according to Fig. 2.56.

The times entered are valid for simply structured situations under daylight conditions and can vary greatly depending on driving and traffic situations. It can be seen that the psychophysical reaction time is around one second. If this one second is converted to metres driven before any reaction happens, then the distance covered in 0.88 sec is 14 m for 50 km/h and 28 m for 100 km/h.

The reason for the relatively long time-lapse is attributed to the line of vision at the moment of perception, since the hazard source is often not pictured foveally on the retina. Further investigations have shown that these times can greatly increase under unfavourable driving conditions (night, lines of traffic etc.) (Schmidt-Clausen 1979).

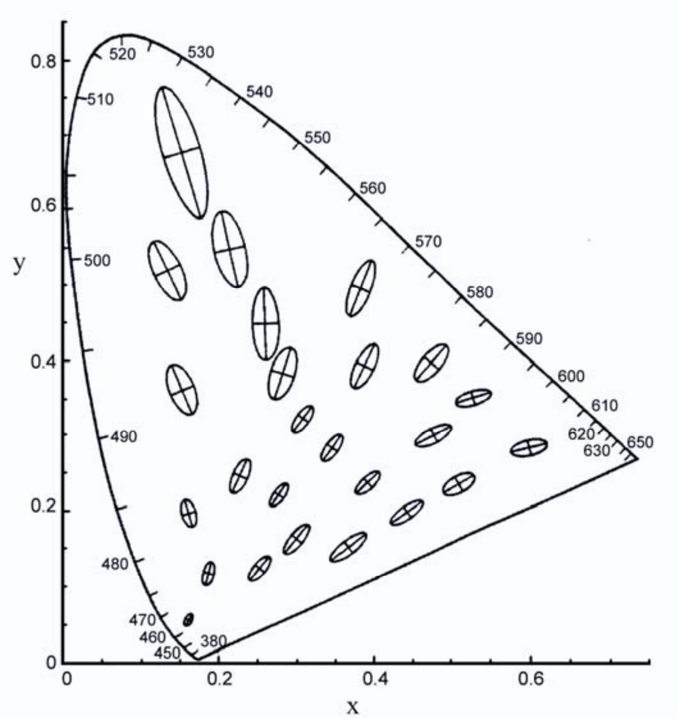


Fig. 2.57 The CIE 1931 x,y chromaticity diagram with the MacAdam ellipses displayed, multiplied ten times (after MacAdam 1942)

Colour thresholds

Both the spatial and temporal thresholds discussed above have been measured using achromatic targets lit by nominally white light, but in the photopic state, the human visual system has a well-developed ability to discriminate colours. Fig. 2.57 shows what are called the MacAdam ellipses enlarged ten times, plotted in the CIE (x,y) chromaticity diagramme (MacAdam 1942). Each ellipse represents the standard deviation in the chromaticity coordinates for colour matches made between two small visual fields, with the reference field having the chromaticity of the centre point of the ellipse. Fortunately, driving does not require fine discrimination between colours. The most that is usually needed is the ability to distinguish between distinct hues that are well separated on the chromaticity diagram, such as the red, amber and green of a traffic signal, or the red and orange of a rear light and an indicator light.

Complexities

All the above capabilities are concerned with detection. However driving involves many other judgements that are not simply see/no see but rather require the perception of various aspects of the world around us. One such set of perceptions involves movement, either of oneself or of other people.

Self-motion

Consider driving on an empty road. As you speed along the road, your visual system receives patterns of movement from the road and from objects alongside the road. These dynamic patterns are known as optic flow.

Analysis of optic flow exposes both the structure of the world around you and your movement through that world. But how do you know that you are moving through the world rather than the world moving past you? The answer is that you do not, at least not from optic flow alone. Other information is necessary to conclude that you are moving through the world, or you have to make an assumption. Among the other sources of information are changes in the vestibular system of the inner ear during accelerating, and vibration felt through the vehicle's contact with the road. If such information is not sufficient, then the usual assumption is that the larger surrounding object (the world) is stationary, and the smaller enclosed object (you) is moving.

Given that you have determined that you are moving through the world, two other pieces of information are useful for the driver, his direction of movement and his speed. Gibson (1950) suggested that the direction of movement can be obtained by changes in the pattern of optic flow. When you are fixating the point towards which you are moving, the pattern of optic flow will be seen to expand if you are moving forward and to contract if you are moving back. Things get more complicated if you are not looking at the point towards which you are attempting to move, because then the pattern of optical flow changes every time you make an eye-movement (Regan and Beverly 1982). There is no doubt that the visual system has a mechanism for extracting the effect of eye movements but exactly how is uncertain.

As for speed, absolute speed cannot be obtained from optic flow alone, because to judge speed you need to be able to estimate distance, which cannot be obtained from optic flow. There are many other visual cues to distance in the retinal image such as perspective, relative sizes of familiar objects, texture gradients and shading and obstruction of one object by another. Of course much of this information is only available when the world through which you are moving is illuminated. Driving at night with headlights alone limits the amount of distance information available and hence makes it difficult to judge absolute speed. This may be why drivers frequently fail to moderate their speed when driving alone on low beam headlights at night.

Relative speed

While absolute speed is of interest when driving on an empty road, if there are other vehicles on the road relative speed is of interest. For example if you are following another vehicle, then as long as the retinal image size is constant, you are both travelling at the same speed and you are neither increasing nor decreasing the distance between you. If the retinal image starts to expand you are closing on the vehicle ahead and the rate at which you are closing is related to the rate of expansion of the retinal image of the vehicle ahead. Of course, how much this change in relative speed matters will depend on distance between you. This is an easy judgement to make when you are close behind a vehicle, even at night because then your headlights will illuminate the back of the vehicle ahead, thereby providing a convenient estimate of distance.

The judgement of relative speed is much more difficult when an opposing vehicle is approaching from a distance on an unlit road. The headlights can be seen as two points of light, the separation between them increasing as the vehicle approaches. The problem for perception is that unless you also have an estimate of distance, you cannot estimate the implication for speed of a given rate of expansion of headlight separation. In the absence of any other lighting, your estimate of distance may have to rest on an assumed separation of the headlights on common vehicles or on what the headlights of the approaching vehicle illuminate. The situation gets even more difficult for a motorcycle when there is only one headlight. Here, if you want to estimate the approach speed you have to detect the increase in size of the single headlight as well as judging the distance.

Spotlight

Optical and kinaesthetic feedback

For researchers studying traffic safety an important question is: How does the driver's brain process the relevant sensory information for the task and how does it control appropriate driving behaviours?

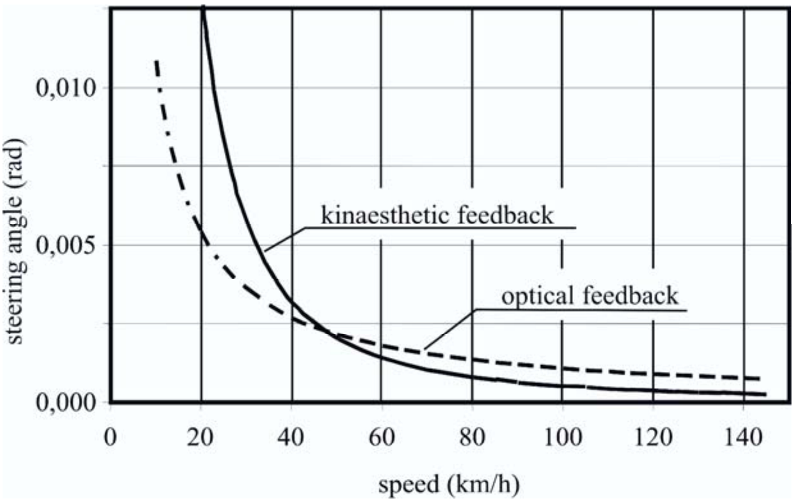


Fig. 2.58 Smallest detectable angle of deviation from a straight course depending on steering angle and speed

We combine information from the various sense organs to a unified recognition of the external world without recognising in some cases, from which sense organs the information comes. The fact that various sense organs have different thresholds of sensitivity can lead to interesting effects. Fig. 2.58 shows the steering angle that gives rise to the smallest detectable deviation from the straight in an arbitrary saloon car. For the calculation of the diagram a dynamic resolution of viewing angles of $\sigma_{min} \approx 2'/s$ (Lindsay and Norman 1972) was assumed and a minimum remarkable acceleration of $a_{min} \approx 0{,}008\ m/s^2$. A deviation of a straight course up to speeds of about 50 km/h is recognised initially optically as shown in the diagram. In the higher speed area the kinaesthetic sensation is dominant. That explains why drivers show a slight zigzag course on completely straight roads (Jürgensohn 2000). The driver sees a straight piece of road, knows that no lateral acceleration is to be expected and regulates the felt lateral acceleration to "zero". As the longitudinal direction of the car can always slightly deviate from the direction of the road he recognises this only when the optical threshold is exceeded. He corrects the course and regulates now again the felt lateral acceleration to “zero” (Gothelp 1984). This phenomenon also explains the reason for the exaggerated steering behaviour in static driving simulators and also the tendency to high velocities that can be observed here.

We should learn the following from these examples - we perceive the external world and our position in it by the integrated combination of the information from all sense organs.

2.3.4 Conclusions

This brief summary of the structure and capabilities of the visual system suggests some questions that anyone assessing the effectiveness of automotive lighting systems needs to ask themselves. For signal lighting the questions are can the signals be seen? and will their message be understood? Answers to the question of whether the signals will be seen can be obtained from the appropriate threshold measurements, only a few of which have been shown here. More complete information on threshold measurements can be obtained in such publications as Boff and Lincoln (1988). As for whether the signal will be understood, that is a matter of consistency and familiarity, both factors involved in the development of the “user interface” of the visual system discussed earlier.

For headlights the basic question is - what needs to be made visible so that the driver can develop a stable and accurate model of the three-dimensional world from the two-dimensional retinal image? Threshold measurements are less valuable for answering this question because what is involved is the integration of information of different forms and from different parts of the visual field, most of which needs to be well above threshold. This is not a problem during the day, but at night it can be problematic when the available information revealed by headlights is inadequate to form a stable image. Considering how to answer this question could cast a new light on the requirements for headlights and any associated mechatronic systems. It would also introduce a more sophisticated view of the visual system than is possible from threshold measurements alone.

3 Automotive Lighting - State of the Art

The history of automotive lighting reaches back for over a hundred years. First of all candles and then gas lights were used for horse-drawn coaches, and gas lights were used for the first cars. In the 1920s electric lights began to be used in cars. Dynamos were installed at this stage solely for electrical lighting. In the thirties and forties optical systems for lighting were developed to include the first projection systems. In the 1950s legal regulations began to cover vehicle lights. In the sixties halogen light sources became available and the voltage was raised to 12 volts. The resulting jump in luminous flux initially caused a public outcry, but was quickly accepted. In the eighties the aerodynamic headlamp began to replace the reflector bulb, also known as 'sealed beam’, which had become almost a standard for headlamps in the United States and Scandinavia. In the 1990s the gas discharge light source, referred to also as ' xenon ' was introduced. It offered considerably more light and almost vehicle life longevity. Headlamp levelling became mandatory in Europe. In the first decade of the 21st century night-time design of vehicles became attractive. Also dynamic headlamps that followed the bends of the road were developed and built into cars. The first night visions systems and the first LED headlamps are being introduced.

Table 3.1 Milestones in lighting

Year	Event
1908	Use of electric bulb in motor vehicle (dynamo, headlamp, side & number plate lamps)
1915	Introduction of red tail lamps and yellow brake lights
1919	Introduction of dipped beams against glare
1925	First double filament bulbs for high and dipped beam
1936	Launch of incandescent sealed beam lamp
1940	Flashing turn signal on front and rear with self cancelling
1945	Integration of headlamps into vehicle body

Year	Event
1908	Use of electric bulb in motor vehicle (dynamo, headlamp, side & number plate lamps)
1960	Introduction of first halogen lamp in Europe
1979	Introduction of first halogen sealed beams in US
1983	Introduction of first composite replaceable bulb lamp in US
1991	Introduction of high intensity discharge (xenon) in Europe
1993	LED tail lamp (Ford Thunderbird – another Visteon first!)
1996	Mandatory headlamp levelling in Europe
2003	First steerable dipped beam headlamps (pre-AFS)

Lighting technology is an exciting field of development. The following section will describe the current state of the art for headlamps, signal lamps and interior lighting.

3.1 Headlamps

Headlamps on vehicles are primarily responsible for illuminating the traffic space in the direction of movement. They must guarantee that the area is sufficiently illuminated using the different light functions, without dazzling oncoming traffic. In addition to this, headlamps should make the vehicle easily visible.

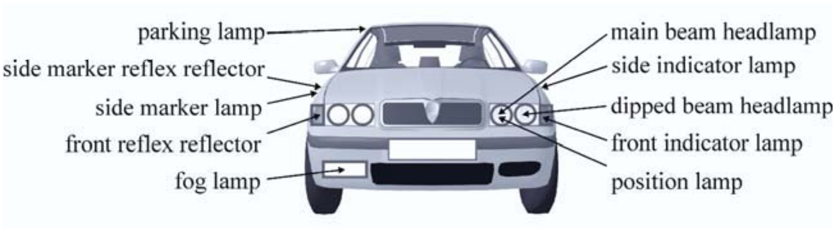


Fig. 3.1 Front lighting as defined within the ECE regulation

A headlamp is a lamp, usually attached to the front of a vehicle such as a car, with the purpose of illuminating the road ahead during periods of low visibility, such as night or precipitation. While it is common for the term ‘headlight’ to be used interchangeably in informal discussion, ‘headlamp’ is technically correct term for the device itself, while ‘headlight’ properly refers to the beam of light produced and distributed by the device.

3.1.1 Installation and function

Legislation regulates the type and installation position of the light function on vehicles as well as their design, light sources, the colour location and photometric values. Fig. 3.1 shows an example of front lighting equipment for cars as determined by European installation regulations.

Legal requirements for automobiles comprise for headlamps dipped beams and main beams, as well as front position lamps and turn indicator lamps. (Dipped beams are also referred to as low beams or passing beams; main beams are also referred to as high beams.) Fog lights, rear reflex reflectors, parking lamps and side marker lamps are, however, optional. Among other measures, the light colour white and installation at a height of at least 500 mm and no more than 1200 mm is prescribed for the two dipped beam headlamps. A static headlamp-levelling device has been compulsory since 1990 in Europe. The photometric details and measuring regulations for the different light functions are determined by the ECE (Economic Commission for Europe), and in the USA by the FMVSS (Federal Motor Vehicle Safety Standard).

The headlamps approved in Europe today allow the driver to choose between dipped beams, main beams and fog lights depending on the individual situation. In Germany, main beams are used in only about 5 % of traffic situations, whereas dipped beams, used about 95 % of the time, are the most commonly-used light function on the road. Fog lights are optionally used in poor weather conditions, such as fog or heavy rain. In Canada and the Scandinavian countries an additional daytime running light is required on the front of the vehicle for improved recognition. Cornering lights, which make sure the road is additionally illuminated when turning corners, were permitted initially in the USA, but now worldwide. Further light functions on the front of the vehicle are the position light and the indicator lights: the function of these lights is not to illuminate the road, but rather to make the vehicle visible.

Light distribution is represented in terms of luminous intensity and illuminance patterns. In accordance with the legal requirements, the values for illuminance are measured at a distance of 25 m (with the exception of Japan and the US). The illuminance distribution is assessed on a wall at a distance of 10 m in front of the headlamp as an additional aid to the discussion and interpretation of the characteristics of light functions. Angle ranges in the light distribution are given by the horizontal H and the vertical V. The figure below shows a schematic view of the distribution of light from the headlamp in the road area with the distribution of illuminance on the 10 m wall and the road. The lines connect points with the same illuminance (Isolux diagram).

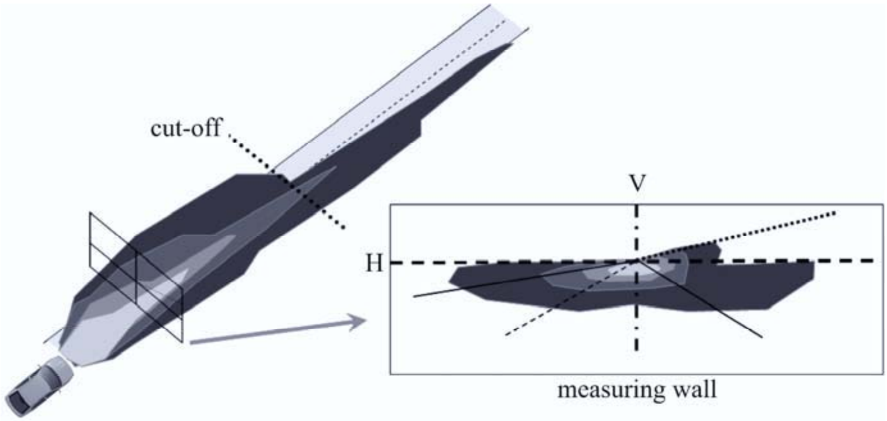


Fig. 3.2 schematic view of light distribution

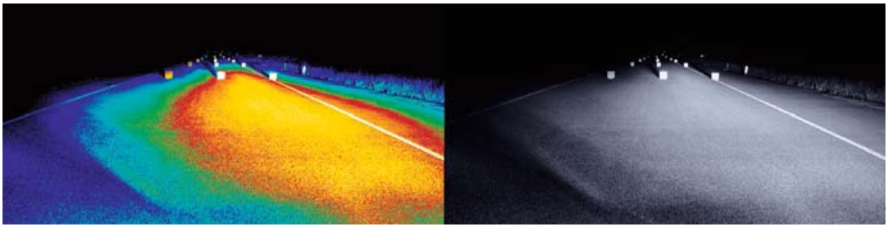


Fig. 3.3 luminance for a car with gas discharge light sources

Taking the grade of reflection from the road into consideration, the driver can benefit from the ensuing perceptive luminance. Pictures of luminance can now be made using modern camera techniques (Gall 1999). Fig. 3.3 shows the example of measured luminance for a xenon headlamp system seen from the driver's position.

The next set of figures compares the light distribution for dipped beams, main beams and the combination of dipped beams and fog lights.

Fig. 3.4 Comparison of dipped beam (top), and main beam (bottom)

This purely visual comparison however, only hints at the detailed demands made on different light distributions. These can therefore be more exactly described as follows. The dipped beams give the driver a large range of vision on his own side of the road without dazzling oncoming traffic.

A sharp cut-off in the light distribution avoids dazzling oncoming traffic. At the same time however, there are minimum requirements on the illuminance above the cut-off in order to guarantee for example the illumination of overhead signs. The 15° rise in cut-off to the right-hand curb (right-hand traffic) guarantees good illumination of the driver’s own side of the road and early recognition of pedestrians, traffic signs and cyclists. Every driver can check the effect of the 15° rise on his or her own vehicle by stopping in front of a wall at night.

The direction of the dipped beam is tilted downwards by at least 0.57°, so that the light thus “falls” by 1 %. This legal requirement means that the horizontal illumination border H, indicated by a horizontal line in figure 3.2, is already 10 cm under the installation height of the headlamps at a distance of only 10 m from the vehicle. This correlates to a maximum range of vision of the headlamp on the oncoming lane of about 60 m – in one’s own lane this range is between 80 m and 120 m, depending on the headlamps.

The main beam is designed for a maximum range without oncoming traffic. For this, the light beamed out is strongly focused onto the road space with vertical scatter widths of ± 10° without any downward tilt. The fog light characteristically produces a large horizontal scatter width (>± 35°). The prescribed downward tilt of 2 % limits its maximum range to approximately 35 m. The fog light illuminates the side areas and the front area particularly well, which leads to better guidance on the road when vision is limited. The luminous intensity above the cut-off has been reduced in such a way that stray luminance is kept as low as possible.

3.1.2 Optical concepts

The generation of light functions with today's headlamps is based on two different technical concepts – reflection and projection technology. The figure below compares two headlamps with dipped beam and main beam functions, thus making clear the combinations and variants of the concepts. While reflection systems stand out thanks to large reflectors behind a clear or patterned lens, projection systems have a small light aperture with a characteristic lens, which can be enlarged by brightening the surrounding area. Reflection systems require less installation depth than projection systems, but are higher and wider.

Fig. 3.5 Two almost identical headlamps with different dipped beams: reflector dipped beam (top) and projector dipped beam (bottom) (source: Visteon)

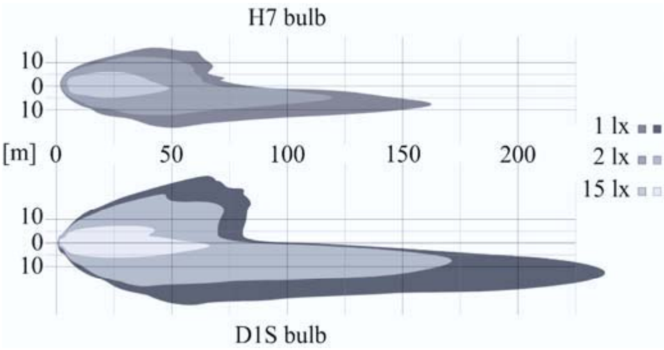


Fig. 3.6 Illuminance of the road for halogen (top) and xenon (bottom) dipped beam

The halogen and xenon lamps serve as light sources for headlamps. Fig. 3.6 shows a bird's eye view of measured illuminance for a halogen and a xenon system in a false-colour diagram. This shows that there is 250 % more luminous flux available when using a gas discharge light source rather than a halogen lamp, which gives the technician considerably more design freedom for the distribution of the light onto the road. In comparison, the better lateral illumination that aids peripheral vision is particularly apparent.

Reflection technology

With the reflection system the light of the bulb is distributed by the geometric shape of the reflector and optional patterning in the cover lens into the road space. A shading cap placed in front of the bulb prevents the direct beaming of the bulb light, as well as the uncontrolled illumination of optically passive surrounding surfaces like decorative frames, both of which could lead to intolerable glare above the cut-off.

Clear cover lens systems are in line with current trends. These employ smooth, segmented or faceted reflectors. In contrast to conventional systems that produce the light distribution via the reflector and then via cylinder or prism lenses, there are no scatter lenses on the cover lens or on any intermediary lens placed between the cover lens and the reflector. The light distribution is thus exclusively produced by the reflector geometry and the shading cap. Today we use computer-calculated free-form reflector surfaces. In the past a simple parabolic reflector sufficed.

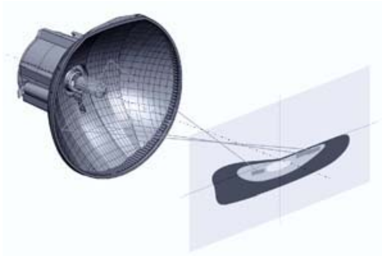


Fig. 3.7 Illustration of the function of a reflector system

Projection technology

The projection system works according to another basic principle, which is clearly shown below. The light of the bulb is first focussed via an almost elliptical reflector in the focal plane of the lens. A shield here limits the light bundle in order to produce the cut-off. The following plano-convex aspherical lens with a typical diameter in the range of 40-75 mm projects the light onto the road.

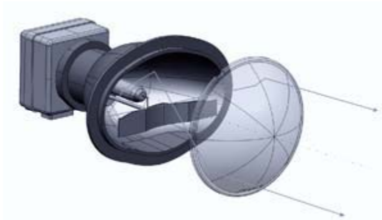


Fig. 3.8 Illustration of the function of a projector system

A characteristic property of the projection system is the colour fringe on the sharp cut-off. It is a result of the colour aberration of the lens and is minimised by adjusting the shading cap in relation to the lens.

Spotlight

Automotive projector modules

History

The basic optical scheme of automotive projectors has been known since the 19th century and was first used in the cinematograph.

The first application in an automotive was at the end of the 1960s – an auxiliary lamp for the Dodge utility vehicle. The first application to main headlamps came in the 80s – Hella and Cibie developed a projector dipped beam module approximately at the same time, and the first car equipped with such a headlamp was a BMW.

With the introduction of xenon bulbs at the beginning of the 90s, projector units became the predominant optical system used for xenon headlamps in Europe. Since then projectors have incorporated more and more functions:

- bi-functional projectors producing a dipped and main beam realising a low and main beam using a movable shutter
- dynamic curve lighting with either halogen or xenon
- new modules with multiple light distributions, such as motorway beam or adverse weather lighting.

Optical scheme and function of projector:

The projector unit consists of 4 main parts: a light source, a near-ellipsoidal reflector, a shield (for dipped beam) and a condenser lens.

The reflector is ellipsoidal in shape and therefore displays two foci. The light source is placed in the vicinity of the first reflector focal point. Light from the source is collected by the reflector and again concentrates near the second reflector focus where the shield is placed. The light beam illuminates the plane of the shield – the lower part of the beam is blocked by the shield, while the upper part proceeds towards the lens. The lens is placed such that its focal plane lies in the plane of the shield. The image of the shield is then projected down the road creating a sharp light-dark transient (dipped beam cut-off line), which corresponds to the shield geometry.

The shield image is reversed (upside down, left to right), which is why the light from upper half of the shield (focal) plane illuminates the road while light absorbed by the shield does not glare oncoming drivers. By moving the shield out of the path of the beam, the whole light beam reaches the lens and light from lower half-plane illuminates the space above the cut-off line. This way a main beam can be produced.

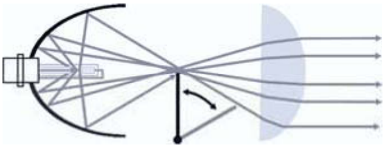


Fig. 3.9 Optical scheme of projector module

Optical design of the reflector

The reflector determines the intensity and distribution of the output beam. For a point light source at the focal point the distribution of illumination (light flux per surface element) over the lens focal plane is projected to the road such that (y, z)-point in the focal plane corresponds to (αh, αv)-direction. This is why the intensity of light from the lens in the (αh, αv)-direction depends on illumination of the corresponding (y, z)-point in the focal plane (see Fig. 3.10).

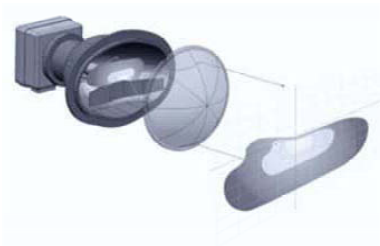


Fig. 3.10 Role of PES reflector for projector light distribution

Fig. 3.11 Principle of PES reflector

To be able properly to manipulate the light distribution, the reflector usually cannot be a simple ellipsoid. The optic designer needs the reflector to “paint” the light distribution onto the focal plane of the lens. Different mathematical techniques or free form surfaces can be used. For example the reflector can be an envelope surface to a set of individual elliptical surfaces, with the first focus in the light source and the second moving along the focal plane of the lens. The surface is sometimes referred to as a poly-ellipsoid surface, or PES. Most lighting CAE software uses direct numerical integration of the reflector surface (or reflector cross-sections) according to the desired individual ray path.

Optical design of the condenser lens

The light beam is strongly divergent after passing the shield with the angle of the light cone approximately 45°. The light intensity is not sufficient for a headlamp. The lens is used to narrow (collimate) the beam especially in a vertical direction to the typical vertical opening of the dipped beam of about 10-15°.

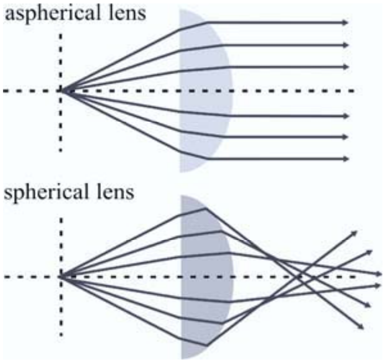


Fig. 3.12 Lens aperture aberration – collimation properties of an aspherical lens (top) compared to those of a spherical lens with same focal length and diameter (bottom)

Compared to imaging optics, condenser lenses used for automotive projectors have a very big aperture angle, typically around 40°(see Table 3.2). A spherical lens with such an aperture angle would suffer from excessive aperture aberration (see Fig. 3.12). Also a spherical lens would not provide sufficient control of glare light, as the shield image would be defocused. One practical solution is an aspherical lens that corrects the aberration. The Fermat principle can be used very well for calculation of a lens cross-section; the lens itself can be a surface of revolution. Such a lens provides a virtually stigmatic image of the shield edge in the centre of the beam and a focal “plane” which is quite curved. For this reason curved shields are used in some projectors. This holds especially if the beam is very wide and the lens aperture angle large. Most projectors for dipped beam can be designed with a flat shield.

The lens is usually planar-convex with the planar surface oriented towards the shield. This set-up is optimal for light efficiency, as light losses caused by reflections on both lens surfaces are minimised.

Using an aspherical lens with very good imaging properties helps to control glare light and creates very sharp light-dark transition (cut-off). In fact, in this case the cut-off line is likely to be too sharp; it is beneficial for the driver's visual comfort to reduce the cut-off gradient. Diffusive texture on the lens surface or a light-spreading wave profile can reduce the sharpness of the cut-off. Currently the state-of-the-art is a lens with the right balance between glare values and driver comfort.

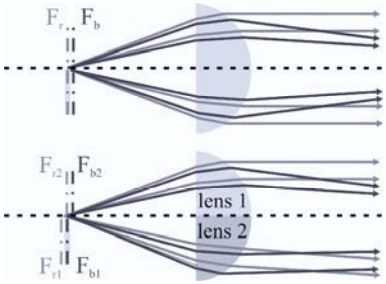


Fig. 3.13 Lens chromatic aberration (top) and the principle of its correction (bottom)

Due to glass dispersion the position of the lens focal point for blue light is closer to the lens than that for red light. (The refraction index of glass changes with wavelength so that the refraction index for blue light is typically higher than for red light- see Fig. 3.13 top). This effect is known as chromatic aberration and can be measured by the distance between the red and blue focal plane. It can cause a noticeable coloured fringe at the cut-off line of the beam, especially when the cut-off line is sharp. Dispersion of light along the cut-off line can be suppressed when the focal points of the top and bottom part are positioned according to Fig. 3.13 at the bottom. In this case the lens is no longer a surface of revolution.

Mechanical design, material choice

The projector module will meet expectation only if the optical system including all parts remains accurate and aligned despite vibrations, changes of temperature and corrosion that may afflict a headlamp. Material selection and manufacturing processes play a key role here and a "design for manufacture" is essential. Besides its performance the price of the product is also important. A more detailed description of projector mechanical layout and property is beyond the scope of this spotlight. A few comments as well as the 'pros and cons' of various options for material choices can be found in Table 3.2.

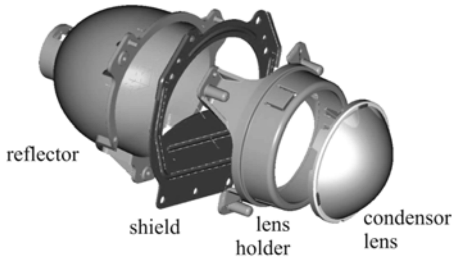


Fig. 3.14 Projector assembly

Table 3.2 'Pros and cons' of various options for material choices

material	highlights	applicability
stamped sheet metal	~ cheap parts but expensive tooling → suitable for high series - limited design freedom - less shape stability + excellent heat resistance	reflector lens holder shield
aluminium die-cast	-- expensive parts, less expensive tooling + design freedom + shape stability ++ heat resistance, dissipation of heat	reflector lens holder shield
plastics (thermoplastic or thermoset)	+ low price (depending on material choice) + suitable for direct metallisation (not all materials) + shape stability (especially thermoset materials) - less heat resistant, poor heat dissipation	reflector lens holder

Outlook for future developments

Several main themes are visible in the development of projector modules:

- Functionality and performance – developing from halogen dipped beam to AFS bi-functional xenon, projectors have now become a common building block for dynamic curve lighting and adaptive lighting.
- Style and appearance – even if the condenser lens should be the only visible part, a lot can be done to differentiate the headlamp and support vehicle style (see figures below).

- Package – especially the packing depth of projectors is critical and a significant length reduction would be a major breakthrough. Some attempts have been made but the disadvantages of solutions proposed so far outweigh advantages.
- Weight - for impact force reduction in conjunction with pedestrian protection the weight of the mechanical design has to be reduced.

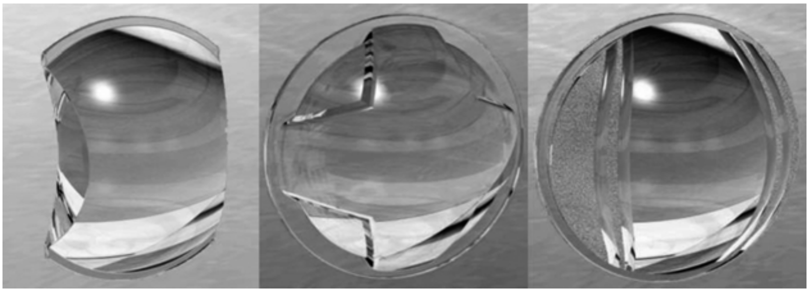


Fig. 3.15 Condenser lenses for style face-lift of a projector headlamp

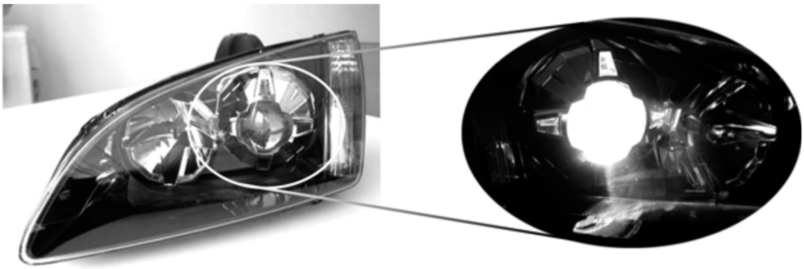


Fig. 3.16 Possible styling of projector headlamp – physical sample, lit appearance (source: Visteon)

Variable beams

The use of modern and highly powerful xenon light sources makes it possible to install highly integrated and multifunctional systems. These are especially suitable for the realisation of the powerful illumination concepts for advanced front lighting systems.

Bi-Xenon systems similar to the one shown above went into series production in 1999. With this system the light of the gas discharge light source is used for dipped beams and main beams thanks to a movable shield in the 2nd focal plane. The shield is triggered by a specifically designed actuator (Wallaschek 1998). In this way two light distributions with a large luminous flux can be realised using little space.

Fig. 3.17 Bi-Xenon projector system (source: Visteon)

Fig. 3.18 Projector system for dynamic bending light (source: Visteon)

An even higher functional integration is possible by installing a system for dynamic bending light. A projector module is put into a frame, which allows it to rotate to the right and left.

The modules for the right and left headlamp are electronically controlled and either move in synchronous mode or are allowed to move independently. In conjunction with dynamic headlamp levelling the dynamic bending functions provide the potential of free movements of the light distribution from the left and right headlamp. This can be the basis for very different adaptive lighting functions from simple bend lighting to predictive AFS or adverse weather lighting.

LED Headlamp

Progress in the development of light sources is making it technically possible to design headlamps with high power LEDs. LED headlamps can differ greatly from conventional designs in styling, packaging and functionality. High-powered LEDs offer the prospect of very dynamic lighting without moving parts. They also offer the possibility to change light distributions gradually.

Spotlight

The emergence of the LED headlamp

All forward lighting functions from dipped beam, main beam, fog lamp, AFS contributors to cornering lighting can be realised using multiple LEDs and optical subsystems. The subsystems generally include optics, mechanical structure, means of heat dissipation and electronic drive circuitry. LED lighting tends to be more complex than comparable forms of lighting due to the multiplicity of sources. Therein however, lies also the freedom, the uniqueness and the challenge for LED forward lighting.

LED headlamp 'living' history

It is very rare to be in an industry at a time of a major technological breakthrough. We are going through such a time with the move towards semiconductor luminescent light sources. The history of the LED headlamp is being written at the same time as this book. It is worthwhile to share an eyewitness account of LEDs in automotive lighting in order to get a feeling of the enthusiasm that accompanies this quiet revolution. The author apologises in advanced for the subjective nature of the report.

Through the 1990's forward lighting was revolutionised by the xenon gas discharge light source. After having made the much earlier migration from incandescent sources to the halogen sources, the step to xenon light sources brought dramatic performance increases to automotive forward lighting. With the much cooler colour temperature than halogen sources and over twice the light output of any other suitable light source, xenon made a noticeable difference on the road.

After xenon was adopted by many European and then Asian luxury brands, lighting engineers worked on the next innovations. Distributed lighting, headlamps with multiple light sources and even laser based lighting appeared in concept cars and on shows.

At the same time, a completely new technology emerged at the rear of the vehicle: light-emitting diodes appeared first of all in high mount stop lamps. For a few years red LEDs had been finding their way into different signalling applications. While other colour LEDs existed, red seemed to be on the fastest path to higher light output. The T-1 ¾ LED package was becoming ubiquitous in many different industries from consumer electronics to display boards and architectural lighting. It provided a convenient package for the small chips limited to about 20mA drive current, as it contained a simple concentrating optics and a pair of legs that made them easily soldered by flow or hand. A couple of spoiler-mounted third brake lights appeared in the mid-90s. The small form factor and light output worked well together here to provide a long, thin array of LEDs to compliment the form of the spoiler itself. Soon thereafter, the 4-post-type LEDs emerged. These new packages offered similar packaging as the T-1 ¾ package, while allowing for more than double the heat dissipation values of their predecessor at a drive current up to 50 mA. This opened up new applications and allowed the number of emitters to be reduced dramatically. At the same time, AlGaAs (aluminium-gallium-arsenide) and then AlInGaP (aluminium-indium-gallium-phosphide) wafer growth improvements provided for increased chip efficiency. This efficiency was enough to challenge Ford to use the new higher output LEDs to light a rear appliqué on the Thunderbird with a beautifully lit and complex optical system. In the late 1990's, as InGaN (indium-gallium-nitrate) wafer epitaxy began to be more widely produced for blue and green LEDs, Nichia's research in blue InGaN epitaxy and experience in phosphors led to the combination of blue chip and YAG phosphor to create white light. Nichia began to produce T-1 ¾ packages using this technology. These devices produced 1 to 2 lm but were limited to about 20 mA drive current. A few years elapsed until other LED manufacturers caught up to create similar white LEDs. But just creating white LEDs through the combination of phosphor and blue InGaN LED chips, while perhaps sufficient for general lighting or other less demanding applications, was not enough. Automotive LED forward lighting required precise optical control and beam shaping, particularly for dipped beam function, which most LED manufacturing processes did not provide. Sometime around 2001, LumiLeds emerged with the conformally coated chip in the Luxeon package. Other manufacturers followed with different approaches within a year or two. Starting at about 10 lm at one watt, it was hard to imagine creating an LED headlamp, since this would still require over 50 devices for a modest dipped beam. However, it quickly became apparent that the year-over-year efficiency gains for blue InGaN chips were much higher than those historically seen for red.

In 1998 we, i.e. Visteon, were engaged by Mitsubishi to assist with the lighting on the SSR show vehicle. It was a crossover vehicle with an edgy look and a large glass tailgate. While we were busy employing the red 5 W lasers we had developed with Coherent to make light guide stop/tail lamps, the designers were busy placing over a hundred Nichia LEDs into a matt black bezel to create one of the first LED headlamp concepts. All were well pleased with the result – a Pace award for the tail lamps and a new watermark for forward lighting concepts – albeit still a formidable distance from feasible.

Fig. 3.19 First Visteon LED Headlamp demonstration prototype from 2002 (source: Visteon)

In 2001 Visteon began seriously creating designs for its first generation LED headlamp, including miniaturised optics to preserve package space, flexible electrical substrates to provide for minimal package depth and elaborate heat sinks to manage the heat the LEDs dissipate. The quest for the appropriate electronic driver for high-powered LEDs also began. The resulting first design contained 30 LEDs for main beam and dipped beam and by simulation and some future projection of lumen output, just about passed legal requirements. The optical design used reflectors and lenses and was relatively efficient with a collection efficiency of 80% and a projected net efficiency of about 65%. The only problem was that the source, i.e. the chip inside the package, needed to be located with a precision of about 20 microns inside the reflector. The comment from the European colleagues, “Where is the cut-off? … I know, but I still don’t see the cut-off…” was something that we thought could be managed in time. Additionally, the lenses were miniature, 5 mm focal length lenses with a unique snap-feature mounting. We began to search the industry for suppliers who could accommodate our temporary fit of insanity. We eventually made contact with workshops for precision optics that scoffed at our loose tolerances, calling our efforts “sloptics”. It worked but we still had to make our product conform to automotive specification in durability and cost – and the suppliers in the heat sink business had no analogous term for “sloptics”. We eventually moulded some parts and metallised them, assembled them and held our breath as we pointed our Mars bar-sized contraption at the wall and lit it up. It bore some vague resemblance to a beam pattern, with eyes squinted and head tilted, but was surely not the requisite component to an acceptable dipped beam. Slowly we realised that the development of LEDs was not going to be the thrilling ride we had looked forward to. The first design cycle was complete. We had created a high precision optical system that had little chance of mass production or roadworthiness.

The next year we began using a completely different optical approach, which predicated a totally different thermal approach, which in turn predicated a totally different mechanical approach, and left only the driver unit as carry-over from the first design. The light sources were now producing 40% more light and the roadmap of the suppliers' promised further increases. We reduced our ambition of efficiency and instead concentrated on keeping tolerances in the range for mass production. With 50% more sources we created a dipped beam close in performance to a halogen headlamp. This time the moulded and machined optics and heat sinks were mounted on a frame for alignment, with an end result that was pretty satisfactory. There was a beam that one could drive behind. Quickly we began to package the optics into the lamp previously intended for our first iteration, and eventually the details were put together. Additionally a pair of the frames was mounted onto a vehicle and the first night drive took place, with satisfactory results. While the output was not going to set the road on fire, it did provide a totally different beam: it was bleach-white and had good spread. However the hotspot did not blend into the rest of the beam at all, making it a little bit distracting to drive.

Fig. 3.20 Visteon 2004 Demo Vehicle with LED Headlamp (source: Visteon)

Meanwhile we managed to entice our first customer to put our first concept, which was at this point all but abandoned, onto a show vehicle for the 2003 Detroit Auto Show. We had to do something with all those pretty lenses we moulded, and there was precious little else we could do with them. We created a design together with the studio designers in California and, after a lot of back-and-forth on the details we began fabrication. It was a headlamp design that not only comprised main beam and dipped beam, but also AFS static bending and light pipe accents. The lamp required individual heat sinks, a monstrous flexible circuit and driver modules that made a package the size of two videocassettes stacked on each other. By the time it came out in the motor show, we had developed the next generation optical system and were well on our way towards packaging it into a US truck lamp – thankfully a segment with lots of frontal area for optics, heat sinks and an appetite for luxury items.

Fig. 3.21 Visteon low beam LED full lens optics headlamp 2004 (source: Visteon)

In 2003 there were a number of other concepts for LED headlamps many of which lacked realism. Over the course of the next year, most major set-makers showed developments of LED concepts.

LED headlamp optical and thermal models

The LED is not a thermal light source. An LED lamp is no longer an optical system that has to withstand the heat of the thermal light source. It is an 'opto-thermo-electro-mechanical' system which must manage the balance between each of the constituents within the adverse conditions of a highly visible, hot, dirty, shaken, stone-pecked and chemical-laden environment. This is an opportunity and an adversity all at the same time.

The optical function is the primary function dominating design. The following optical systems offer themselves for an LED headlamp:

- Reflector optics benefits from well-tuned tools and methods of beam control
- Projectors were adapted to the luminous intensity distribution of LEDs. New lens designs emerged to make use of the lack of infrared emission and the improved distribution of heat.
- Lens designs make use of optical systems already seen in remote lighting systems. Because of the lack of infrared radiation the light of an LED can be coupled directly into lenses and light guides. This allows novel optical systems involving 'one-sided' lenses, thick light guides, total-internal reflection, multiple optical surfaces and even micro-optics.

The thermal function is the secondary function, which strongly determines the design. Overheating of the LED is a big concern and limits the power put through the diodes. Considerable work is therefore going into the management of junction temperatures and thermal conduction coefficients of the light source. The headlamp has to operate over a range of temperatures from -40°C to in some cases over 120°C. Two main thermal problems need to be solved in the headlamp:

- stopping the light source from overheating and
- de-frosting or de-icing the headlamp lens.

Most designs contain ample passive heat sinks. For a more compact headlamp active cooling using fans or heat-pipes are considered.

Continuing development of the LED light source is slowly making the integration task easier. The temperature resistance of LEDs is improving. The colour tolerances in the production of high power white LEDs are becoming more and more accurate and solutions to handle the variation in forward voltage and flux are emerging.

Fig. 3.22 Cadillac STS with Visteon LED Headlamps, 2005 Demo (source: Visteon)

Outlook for the LED headlamp

The LED headlamp has a bright future. Limitations that once plagued the implementation of LEDs in a headlamp have largely receded: output has increased, packages have become more suitable, brightness has risen and there are many options for optical coupling. The remaining hurdles will shrink over time with the continued increase in efficiency, durability and light quality of the sources as well as experience and optimisation of the systems that accompany them and the electronics that drive them.

3.1.3 Design aspects of headlamps

The task of headlamp development is constructively to put into practice an optimal compromise between the following main requirements: technical performance (luminous flux, efficiency, light distribution); design (appearance when illuminated and not illuminated); quality (process safety, durability, reliability); vehicle integration (weight, size), development time and development costs

Design principles, legal requirements and expertise in the field of headlamps have been established thanks to continual development and numerous inventions over the decades. Innovations have pointed the way to headlamps, which can change their light distribution and adapt it to specific driving situations (with the aid of a high integration level of electronics).

Structures and systems

Thanks to the variety in the number, form, connecting structure and characteristics of the structural and connecting elements of cover lens, reflector and housing or supporting frame, many different structures are possible.

The inclination of a headlamp relative to the road must be adjustable. In order to do this the headlamp must be built in such a way that the reflector can be moved either alone or together with other parts of the headlamp. In housed headlamps the reflector is moved within the housing. A headlamp-levelling device can be integrated into the housing. The movement does not change the gap between the headlamp housing and the car body. For this reason housed headlamps have the advantage of a clean edge to the car body with relatively small gap size. Headlamps in which the reflector and cover lens unit can be moved in just a frame are called supporting-frame headlamps. These simplify installation. For example a hybrid design with a cover lens partly fixed to the car body and a reflector, which can be partly adjusted, is used for several types of fog light. The reflector is moved and sealed against the housing by an adaptive-adjusting seal.

Headlamps are categorised by the number of beams or reflectors used. In a dual-beam system – the number always indicates the number of headlamp reflectors on the front of the vehicle – both the reflectors are used for the main beam and dipped beam functions. Such systems are typically fitted with dual filament bulbs, for example the H4. On many vehicles the dipped beam or a combined dipped / main beam is produced using two reflectors, while two further reflectors are used to build up or complete the main beam. Such systems are consequently classified as four-reflector or 'quad beam' systems. In a six-reflector system there are either additional fog lights or a further function reflector integrated in the headlamp. Depending whether the contacts of the light sources to the vehicle supply system are individual or via a central plug results in outer contact structural shapes, or centrally contacted headlamps which have an internal wiring harness and only one plug.

Moreover, a headlamp can only fulfil its primary task of providing illumination if the right components are used to guarantee the secondary functions of the headlamp. Important secondary functions are: connection of the headlamp to the car body, basic adjustment of the optical systems to the vehicle, sealing and ventilation of the headlamps, cleaning of the cover lens, possibility of replacing the light sources, electrical connection of the light sources, headlamp levelling function and if necessary the electronics for supplying the light sources. The figure below presents the structure of a typical headlamp. Housing and car body are marked dark, connecting elements grey and functional parts and groups in light tone.

There are many reasons not to develop every device completely from scratch, but instead to integrate qualified parts and components into a modular concept, which can then be combined to give an individual appearance. In this way we can present new technologies more quickly, realise variants more easily, reduce development risks, utilise synergy effects thanks to larger quantities, look at concepts more quickly and in more variety or use established specifications and interfaces.

Important constructional aspects of some of the headlamp components are summarised in the following:

- Reflector
  Reflectors are made of plastic (Duroplast, Thermoplastic), sheet metal, glass, aluminium and, very recently, from magnesium die-casting (Kalwa 1999) as well. Depending on the surface structure of the material, the reflector is either coated with aluminium directly or coated with a primer beforehand. Subsequently it is always coated with a protective layer.
- Projection module
  Due to the exactly delineated beam paths and the high level of luminous flux, projection modules are becoming more and more important. A modular system is emerging with different lens diameters, light functions and connection systems from which highly individual headlamp concepts can be generated, although the modules themselves are highly standardised.

- Housing
  Polypropylene with different filling materials, including among others glass-fibre reinforcing, is mainly used as a housing material. Important optimisation possibilities with regard to weight, use of material and cycle time are the result of mould-flow analyses and stiffness calculations with the aid of finite-element-method (FEM).
- Cover lens
  Cover lenses made of glass (mainly out of soda-lime) moulded into shape from the melted mass were used for a long time. The development of optic-free cover lenses however, has meant that polycarbonate lenses have become today's standard. Coating systems that are scratch-resistant have made it possible to use these PC lenses in accordance with ECE and SAE regulations. In comparison to glass, plastic lenses have the advantages of higher resistance to impact, lower weight, small manufacture tolerances and much greater freedom of design thanks to the possibility of undercuts.
- Adjusting elements and headlamp attachment
  Highly standardised components and established process steps mean that installation is quick, precise and safe, making readjustments possible in case of dislocation of the cut-off during the vehicle's lifetime, or after a bulb has been changed.

Headlamp cleaning

Headlamp cleaning systems have been in use since the 1960s. In Europe a headlamp cleaning system is mandatory equipment in conjunction with xenon lights. The units use a high- pressure water jet to clean the cover lenses thoroughly and effectively without damaging the surface. The system typically consists of: whirl chamber jets which are either stationary or telescopic, and which produce different water distribution patterns; low-loss, pressure- or displaced-controlled relay valves; a group of hoses; a water tank with centrifugal pump and a consumption control device in the form of an electronic time control unit or a relay. The headlamp-cleaning unit usually works with the dipped beam switched on and by operating the washer pump of the windscreen wipers.

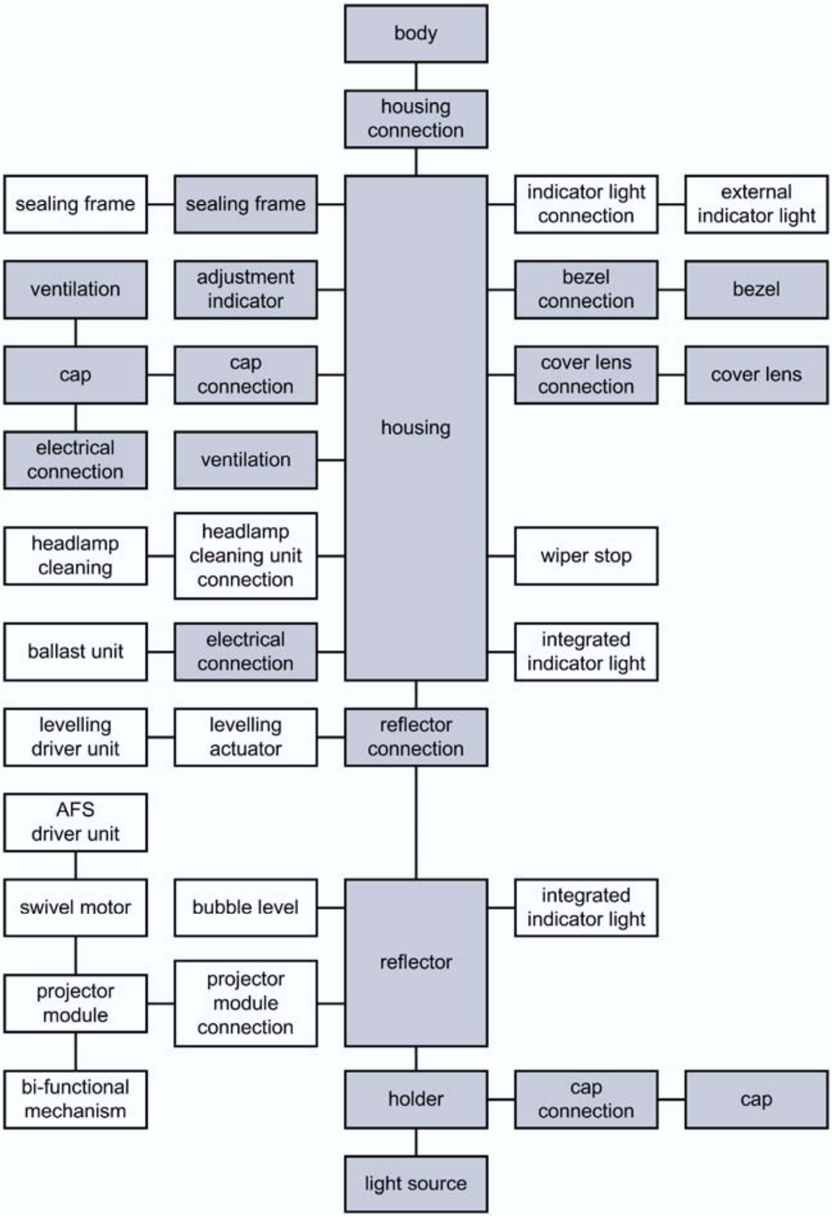


Fig. 3.23 Block diagram for the different headlamp components

Headlamp levelling device

Safe driving in the dark is only possible with headlamps whose angle of tilt is always correctly adjusted. Today's European legal requirements for the manual control of the headlamp level for halogen headlamps mean that the driver can adjust the inclination of the headlamps according to the individual load situation, using a switch on the dashboard. The movement of the reflectors or the reflector-bearing frame in the headlamp housing is usually effected by means of electric actuators. Automatic headlamp levelling device systems are mandatory in conjunction with xenon in Europe. They adjust the headlamps' angle of tilt to the vehicle's road position without driver intervention.

The static automatic headlamp-levelling device corrects changes in inclination caused by changes in load. In addition the dynamic headlamp-levelling device reacts to changes in inclination caused by accelerating and stopping processes. Sensors on the axles send the suspension movement signal to a control unit. This calculates the required headlamp angle taking the condition of the vehicle into account, and then sends the appropriate control signals to the headlamp-levelling device. This means that the driver has an optimal view without dazzling oncoming traffic.

Fig. 3.24 Illustration of the safety gain with dynamic bend lighting (source: Visteon)

Dynamic headlamp control

Before 2003 only the main beam was allowed to be rotated with steering angle. In 2003 the ECE regulations were changed to allow the dipped beam to follow the curvature of the road.
The control of the headlamps has to be very precise and requires input for the steering angle and speed of the car. With increasing detail of digital map data and the emerging use of forward looking cameras, the headlamp beam is allowed to swivel into the bend ahead of the vehicle.

3.1.4 Quality in development and production

In addition to the technical design and sample testing of the optical systems of new headlamps, the technical quality of lighting products is mainly achieved thanks to a high quality of production. In addition approval tests, random sampling tests that accompany series production, together with occasional 100% fully automated assembly line checks, guarantee the high quality of our products.

Spotlight

Are my headlamps any good?

Headlamps illuminate the road ahead when it is too dark to see without them. The simple way to test their function used to be:

- Switch them on. If you notice they make a difference then they must be working.
- Switch on the main beam and see whether this makes a difference. If the main beam is brighter, then that must be working too.
- Start driving- if other drivers coming towards you flash their lights, then you have either forgotten to dim the main beam or your dipped beam is aimed too high. If no one complains, then most probably the headlamps are in dipped beam and aimed correctly.

So you think, and so it might have been some time ago. To know whether your headlamps work and, more to the point, whether they are any good, is an entirely different matter. Also it is a mistake to believe that your headlamps are high performance just because the car is.

Headlamps have become more and more complex

The evolution of headlamps first brought us main beam, dipped beam and fog light. The next refinements came with headlamp levelling and cleaning. Then new light sources such as halogen and high intensity gas discharge lighting (xenon) opened up new levels of performance. Now bend lighting and adaptive front lighting systems are beginning to populate cars with new functionality. So how can you be sure that your headlights work? And how do you ascertain that you get best support for your own vision, whilst avoiding glare for oncoming drivers?

For a closer inspection of headlamps it is advisable to check separately for appearance defects, malfunction and lighting performance rating. Typically journalists carry out these checks when they compare vehicle performance. In some countries the transportation authority checks vehicle lighting. You may also remember some of the advice your driving teacher gave you.

Checking for visual defects

Headlamps used to have glass lenses. Once a stone chipped them, they tended to break and force the driver to replace the headlamp. Today, with plastic headlamp lenses this is no longer the case. The headlamp lenses may be chipped and water may leak into the headlamp, thus leading to corrosion and finally, dulling of the reflector. Therefore, as the driver you are well advised to check for:

- Cracks in the headlamp lens
- Signs of water ingress, such as droplets on the inside of the lens
- Corrosion on the reflector
- Dulling of the headlamp lens due to scratches or excessive exposure to UV light

Note: a small amount of condensation on the inside of the headlamp need not necessarily be a sign of deterioration. The headlamp is an open system and will always contain a small amount of humidity, which under certain conditions will settle on the inside of the headlamp lens as condensation, typically a light haze in the corners of the headlamp lens.

Checking for malfunction

Headlamps are electrical devices with typically two states: On and Off. Hence for the headlamp to work it is easy to check the main functions by turning the lights on:

- Check dipped beam ‘On’. Driving with only one headlamp working properly is likely to be confusing for other road users. You don’t want to be mistaken for a motorcyclist!

- Just as important for other road users is the correct functioning of the position lights. They should be on at the same time as the dipped or main beam.
- Check the indicator. In most countries the indicator is checked electronically. The indicator signal on the dashboard and the accompanying acoustic signal run at a considerably higher frequency when the system diagnoses a failure.
- Check main beam ‘On’. Note: some cars continue to operate the dipped beam with the main beam.
- Check fog light ‘On’. Note: in many countries the fog lights only come on in conjunction with the dipped beam.
- Perhaps you are lucky and your car has lights on even during the day. The ‘day time running light’ or DRL is an additional safety feature favoured strongly in countries with extended periods of low light levels. Cars with DRL tend to be more conspicuous in low contrast conditions. Check whether you have daytime running lights and whether they are working.

Note: some cars will automatically check the correct workings of the bulbs for you, so you do not actually have to get out of the car to see whether the lights are on. However you may still have to activate the relevant light switches for the electronic check to occur.

Lighting performance rating

In typical driving situations in Europe, North America and Asia, the dipped beam is used for more than 90% of the time. If you are concerned about lighting performance and how good your headlamps really are, then you might like to concentrate on the dipped beam. Note: in remote locations such as the Australian outback or the northern wilderness of Finland more extensive use can be made of the main beam. If you are concerned about main beam performance, a slightly different set of criteria for rating applies than that described below.

Professional lighting engineers for headlamps tend to measure the lighting performance on a goniometer, or evaluate the light with night drives. They prepare tracks for measurement of specific lighting aspects, such as recognition distances. As you are unlikely to have the necessary equipment, you are unlikely to reach an absolute assessment of lighting performance. This should not stop you from gaining an understanding of the relative performance characteristic of the headlamps on your car. Why not start with an assessment of stray light, that is to say the light that unintentionally escapes your headlamps. You can check this in your garage:

- Check for stray light. The dipped (or main) beam should light up the garage wall in front of the car. A good headlamp will also light up the side walls a little all the way round to the driver and passenger door. A small amount of light to the side is essential for the perception of speed. Streaks of light on the sidewall however, may be detrimental. The lighting engineers refer to them as ‘cats’ whiskers’. The more pronounced they are, the more the driver is distracted. Stray light directly in front of the vehicle and on the garage ceiling is usually harmless to the driver. It can be an indication of careless engineering and is a waste of light that could serve a better purpose.

For the next stage of performance measurement, find a quiet and preferably unlit, dry road. Here you can park the car safely and switch through the different lighting functions, without irritating or endangering other drivers. In many countries the road markings are set at specific distances that allow an easy first check of lighting:

- Check headlamp aim. The dipped beam of the vehicle should light up the road to between 65 and 110 m in front of the car. If your headlamp falls short or exceeds these limits, then check and adjust headlamp levelling.
- Check side illumination. The headlamp should have a different reach for neighbouring lanes. For the left lane i.e. typically for oncoming traffic, the dipped beam should still be noticeable between 20 and 30 m ahead. For your own lane, the beam should be noticeable up to about 60 to 80 m ahead. On the verge to the right, the beam should reach even further.
- Check glare. Not many people check their headlamps for glare. This has a hidden advantage, because you actually have to get out of your vehicle, and are not very conspicuous to other drivers whilst walking around and in front of your car. Try not to get yourself run over or have your car stolen! About 50 to 70 m in front of the vehicle you will notice that the headlamp beam will just light up the bottom of your trousers. When you look back at the headlamps you should not be blinded. As you look back and gradually stoop lower, you should notice an increase of the beam intensity. For a headlamp with ECE approval the increase should be sharp and very noticeable. For a headlamp with SAE approval the increase will be more gradual.

Note: the headlamps of your car have to fulfil a number of different functions. The figure below illustrates the main lighting tasks:

1. fixation area – should be bright (note: for ECE headlights between 25 and 65 m, for SAE headlights between 40 and 90 m)
2. fore-field – should be fairly homogeneous but not too bright
3. right lane markings or verge – should be fairly bright and reach far
4. orientation and left lane markings – should be fairly bright, but not reach too far
5. road signs – modest illumination
6. area for overhead signs – a little illumination

7. minimal glare for oncoming drivers – practically unlit.

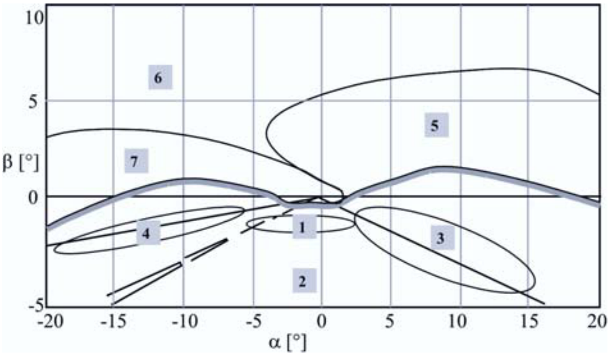


Fig. 3.25 Areas of attention for dipped beam performance

Outlook

What you buy is what you get. You are better off if you buy a car with quad beams instead of the more standard combined low and main beam. The law in most countries allows you only one pair of dipped beams. So you are stuck with what the car manufacturer offers you. If you ordered high intensity discharge lights instead of halogen headlamps you are better off than most people. If you drive in areas with little traffic you can always resort to an auxiliary set of main beam lamps.

If after all this you now know that your headlamps are poor, then we can safely say: better luck next time!

Quality of light

Special lighting software makes the optimised design and early analysis of technical light systems possible. This software is like a virtual lighting laboratory and includes various calculation, modelling, simulation and analysis tools. The basic components of the virtual lighting laboratory have been derived from the most important, optically effective modules of the headlamps which include: light sources, reflectors, shading caps, lenses, cover lenses or intermediary lenses, and geometric shape of the surrounding area.

A background simulation is built up by the editor from the basic modules. Detectors are then added whenever luminous flux, illuminance or luminous intensity and/or luminance are required. Subsequently light beams originating from the light sources are produced in the simulation and registered by the detectors.

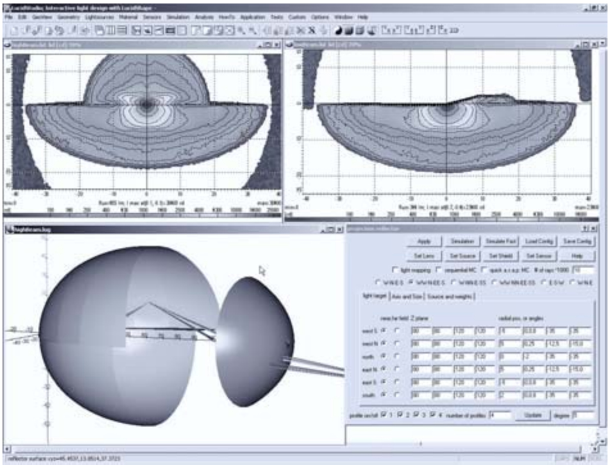


Fig. 3.26 Visualisation of optical system performance during development using Lucid Shape

On top of this, expert systems allow the power of headlamps and bulbs to be initially estimated according to dimensions and peripheral conditions.

Mechanics

Switch fatigue tests and vibration tests are important elements of mechanical headlamp testing. Depending on customer specification, switch fatigue tests in particular are often carried out in combination with temperature and climate tests. Vibration tests check the stability of the devices and are driven over impact and shaking equipment. The widening of the light-band in driving mode and other criteria are checked using specifically varied frequencies and amplitudes.

Spotlight

CAE in exterior lighting

This spotlight describes how virtual prototyping can be made to work for exterior lighting using computer models and finite element or the finite volume methods. The industry likes to refer to "CAE", or Computer Aided Engineering, which means the support of design via computer calculations. The advantage of the CAE systems is virtually to simulate real boundary conditions, for example static, dynamic, and ambient heat, and to determine the behaviour, such as deformation, stress or heat displacement, of a new part in the concept design stage. The new part has to fulfil the requirements which have been defined in the given specification. Using the CAE results, this part is approved or design changes are recommended to fulfil the specification.

With CAE the fulfilment of these requirements can be already verified in the concept design stage when no real parts or prototype parts exist yet. The method helps to decrease the number design changes in the later stages of development. By means of CAE simulations the number of real tests is reduced. The great advantage of CAE, however, is the possibility to compare more variants in a relatively short time and thus optimise the design at only a modest increase in development cost.

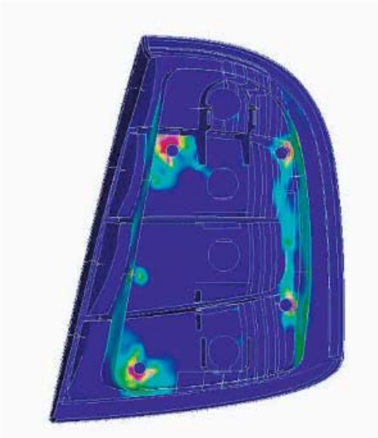


Fig. 3.27 Early CAE Model of tail lamp housing for virtual testing (source: Visteon)

History

Before CAE there was only one possibility of checking the feasibility of new designs. This was a test on a real product or prototype. It was time consuming and expensive. With the development of mathematical methods based on finite elements or finite volume methods, and computers, a huge development of virtual testing methods for new products began. This virtual testing is much faster and cheaper. Also we can check more possible solutions or find out the optimal solution from the point of view of defined boundary conditions. CAE started in earnest in the 1980s and since then has become an integral part of product development. The systems have improved and now integrate into the CAD design suite of programmes allowing for CAE methods to be applied to designs as they evolve. The tail lamp

in the figure below shows an early project which was fully supported with CAE virtual testing.
The following tests and analysis are done with CAE systems to support the design and development of headlamps and tail lamps.

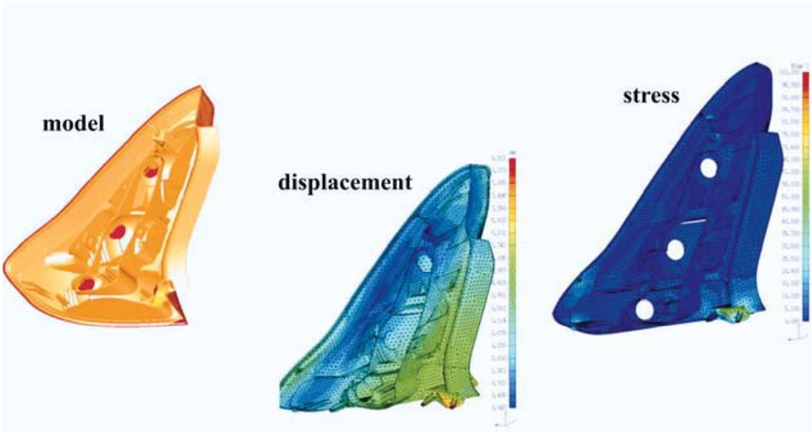


Fig. 3.28 Deformation of tail lamp under assembly torque (source: Visteon)

Structural analysis

Structural analysis checks for deformations and stresses under static load such as forces, torques, pressures or displacements. For special materials e.g. rubber, non-linear analysis is used. Geometric non-linearity is used to compute for contact situations. The analysis leads to recommendations for design changes at critical places. Typical examples are the attachments of tail lamps into a car, the checking of clips or seals.

Vibration and durability

When checking vibrations the engineer first of all looks for the natural frequencies of the object. The ‘Eigen frequencies’ and ‘Eigen modes’ are computed under dynamic loads. This allows the identification of the weak points in the design. An expert can use the information to make design recommendations which improve the stiffness at critical places. Long term vibration effects are analysed by looking at the critical parts under harmonic or random excitation load. This provides a good indication for the durability of the parts. Typical concerns on headlamps are the forces generated due to low frequency resonance. Long term exposure to vibration challenges the headlamp in areas like the bulb shield or the reflector connections for levelling.

Fig. 3.29 Eigen mode analysis of headlamp (source: Visteon)

Heat and moisture

The effects of temperature from the light sources are considerable. A typical incandescent lamp converts over 90% of the electrical energy into infrared radiation and body heat. Conduction, convection and radiation of heat and airflow management inside the lighting product are all calculated.

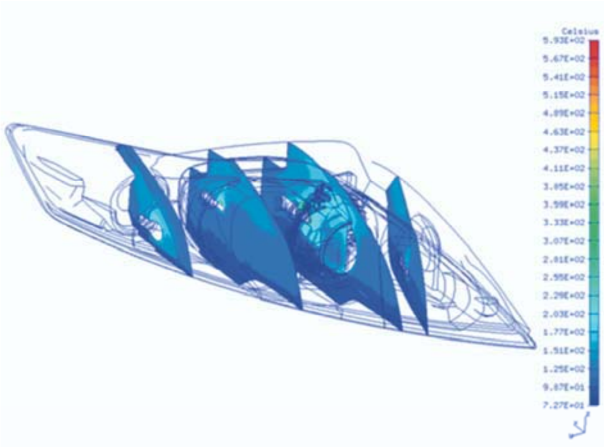


Fig. 3.30 Heat layout in headlamp (source: Visteon)

Almost all headlamps have vents which connect the inside chamber to the outside air under the hood. The air is encouraged to circulate in the headlamp in order to avoid critical parts from overheating. The material for each part is checked and approved according to the heat requirements. Critical areas in the headlamp are the top of the reflector above the bulb and the front lens at areas of high illuminance. The air flows through areas with different temperatures and pressures. Analysis can predict critical places where moisture in the air is likely to condense. Typical areas that are affected by moisture are the colder pockets of the headlamp lens.

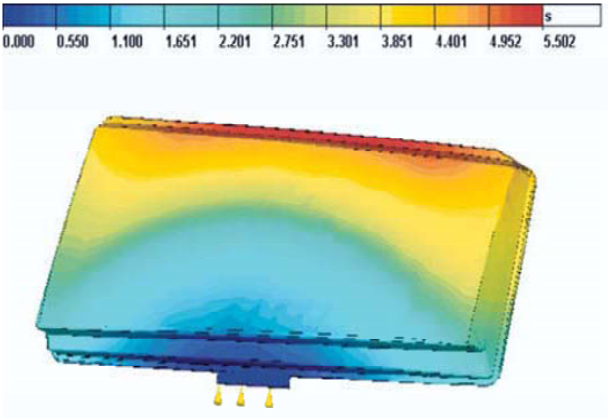


Fig. 3.31 Mould-flow analysis of cap (source: Visteon)

Mould-flow

The mould for the part is designed and optimised using mould-flow analysis. The computer details the filling of the form at different stages. This is a good check against unwanted weld lines or air traps. Further information on temperatures, pressures and shear stresses tell the expert about the quality of filling. Typical areas of concern are ‘dieseling’, i.e. ignition without spark, of duroplastic mould processes and uneven loads on the tool.

Fig. 3.32 simulation of child head impact of front end of the car (source: Visteon)

Impact and crash test

The European regulation 2003/102/ES for pedestrian protection requires another design check for headlamps. A typical analysis includes the simulation of child head, upper leg and lower leg impact. Forces during impact are limited not to exceed a given maximum. Areas of concern are stiff corners of the headlamp lens and heavy projector modules.

Mechanisms and actuators

The functionality of the new designed mechanism for automatic levelling and dynamic bending can be simulated. This allows the calculation of forces and accelerations within mechanism and finally qualifies feasible solutions for a new mechanism. Typical areas of concern are hysteresis of actuators and cross axial forces.

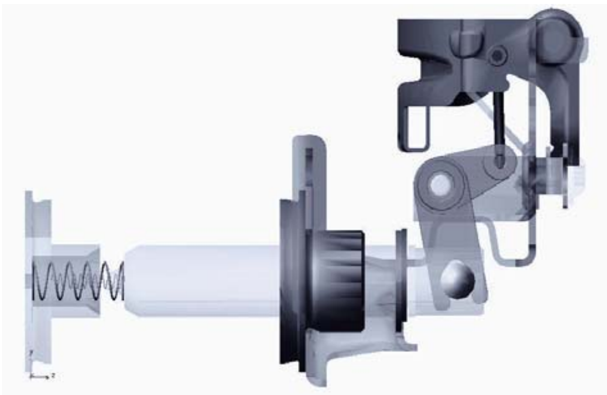


Fig. 3.33 The bi-functional mechanism of dipped/main beam projector (source: Visteon)

Optimisation

Recent advances in CAE systems now show shape and topology optimisation for simple parts under load. The topology optimisation calculates an optimised 3D shape of the solid part under static load. It will also remove unnecessary space from a part. Moreover the stiffness is increased in accordance with the Eigen frequencies and modes. Typical areas of application are material and thickness of complex parts.

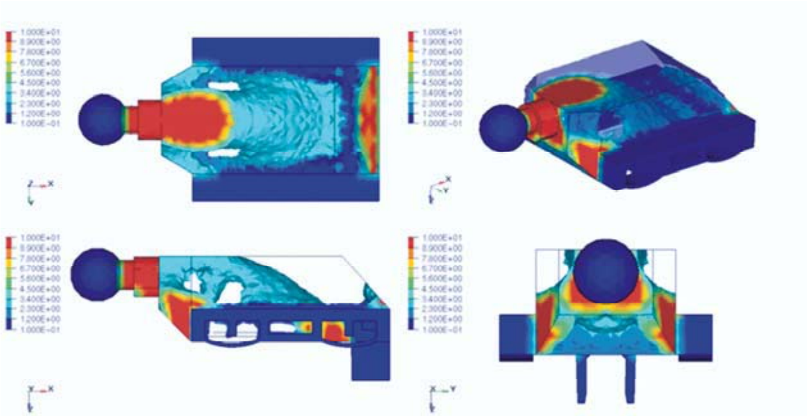


Fig. 3.34 Topology optimisation of adjusting bracket (source: Visteon)

CAE software integration

A typical CAE analysis is divided into 3 or 4 individual steps:

- Pre-processing: The design geometry is converted into a mesh of small elements, the finite-element mesh. Loads and constraints are applied and material properties fixed. The mesh is intentionally made finer in areas which are considered critical or where complex loads are applied. In other areas the mesh is left coarse.
- Solving: The numerical analysis take the mesh, loads, constraints and other parameters to work out specific design attributes such as stresses and strains, temperatures or displacements as described above.
- Post-processing: for viewing and data extraction follows the analysis. The viewing software allows the engineer to interpret the different aspects of the design together with the result from the numerical analysis.
- Incorporation of samples: in some cases a small simulation is used to work out material parameters. The correlation with measurements of samples is used to verify or calibrate the parameters.
- Feedback from measurement data: it is important to cooperate closely with the reliability and testing group to compare the predicted CAE results with measured data. This allows the further improvement of the precision of the CAE models and this increases precision and reliability of the predicted CAE results.

Outlook

The most time-consuming part of CAE work is creating a meshed model of the real part in the pre-processing phase. Creating finite element or finite volume models is becoming more and more automated. The aim is to mesh automatically whilst fulfilling the required mesh parameters. Also morphing will be used to create more modifications or optimise the final mesh with respect to some parameters. This will significantly increase the speed and effectiveness of CAE work. The meshed models will be more detailed-millions of elements will not be uncommon.

The implementation of this huge model will need 64-bit operating systems and hardware. This will allow huge model sizes and they will be solvable.

The main focus of work will shift from pre-processing to post-processing. It will result in speedier modifications or further design choice for more optimal modification, the correct interpretation of results, or the creation of know-how databases for each analysed subject.

Temperature

As constructional volume is becoming more and more limited and temperatures under the hood are increasing, the developers of headlamps are paying special attention to the distribution of temperature in their devices. Temperature prognoses on the basis of calculations have reached a high degree of reliability. However, all devices still have to qualify according to customer specifications in extensive tests carried out under realistic conditions.

Climate and ventilation

Climate checks determine the behaviour of the material at high relative humidity and sunshine levels, and serve to optimise the ventilation of the headlamp in order to avoid long-term condensation on the cover lens when driving, even in critical weather conditions. The design, which is becoming more and more compact (with the narrowest of air gaps on the inside of the headlamps, together with the very tight fit of the headlamps to the car body), makes it difficult to guarantee good ventilation and thus avoid condensation on the cover lens. Air flow simulation helps in the early phase of a headlamp’s development to recognise favourable conditions for effective ventilation.

Spotlight

Fogging and de-fogging of headlamps and tail lamps?

Introduction

Headlamps and tail lamps are usually not hermetically sealed. Air can flow into and out of the system. Depending on temperature and weather conditions the air flowing into the system could be warm and humid and as a consequence, water can condense on the cold surface of the outer lens, as in Fig. 3.35. For this reason specific designs have been developed to avoid the so-called “fogging”.

Fig. 3.35 Water condensation on the outer lens of a headlamp

Condensation occurs when the temperature of humid air falls below dew point. Fogging of a headlamp or tail lamp is in principle, the same process that can be observed when warm air from the shower contacts a cold mirror in the bathroom. Fogging of headlamps typically occurs after a car wash or in cold humid weather when air heated by the motor enters the headlamp. If the system is properly designed the condensation films will quickly disappear when the vehicle is driven. Here the altered air flow conditions strongly affect the thermodynamics of the system.

State of the art

Factors affecting fogging and de-fogging

The processes involved in fogging and de-fogging are numerous and complex. Condensation can appear in the form of continuously distributed films or in the form of isolated droplets. It can therefore best be described verbally by its appearance (film or isolated droplets) and its extent (isolated condensation spots or large condensation areas).

The factors affecting fogging and de-fogging, see Fig. 3.36, include, among others:

- weather conditions (temperature and humidity of the ambient air)
- flow rate and velocity distribution of the air stream

- geometry of the headlamp chamber
- material properties of the housing (water storage capacity)
- lights on / off

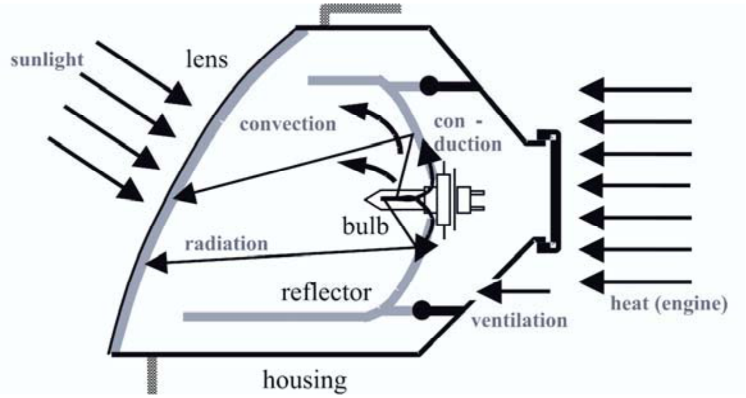


Fig. 3.36 Thermodynamic model of the headlamp system including factors affecting fogging and de-fogging

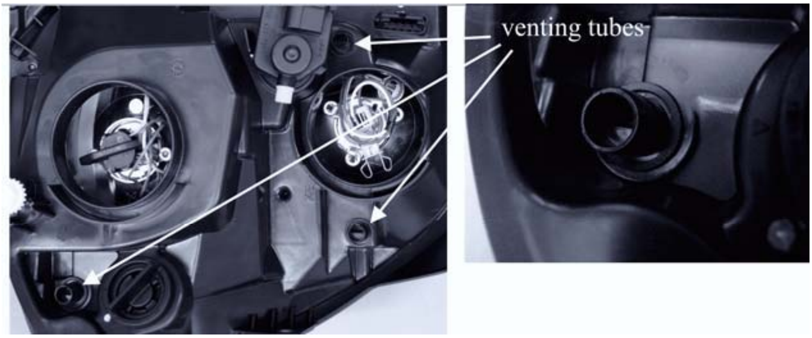


Fig. 3.37 Headlamp and its venting tubes

Specific design elements can be used to influence fogging and de-fogging. The most widely used solution elements are venting tubes which are placed at specific locations of the housing. The length and diameter of the tube, as well as the properties of additional rubber or foam elements, which are placed in the cross section area, can then be varied in order to change the air flow into and out of the system, see Fig. 3.37.

Consequences of fogging

It is interesting to note that the type approval of headlamps and tail lamps is based on the performance of the new clean system. Fogging therefore has no “legal consequence” on the behaviour of the headlamp or tail lamp. However the technical consequences of fogging must not be overlooked. A condensation film on the outer lens will of course, change the light distribution, as the film absorbs light and produces incoherent scatter. In most practical cases however, the effects are not very pronounced. Fogging of headlamps and tail lamps therefore, is more a problem of appearance rather than one of safety.

A common performance measure for the quality of a headlamp design with respect to fogging and de-fogging is to drive the car through a car wash under standardised conditions and to measure the distance that the car must be driven before the fogging completely disappears. The result of course, also depends on the weather conditions, so that these tests must be carried out under standardised weather conditions.

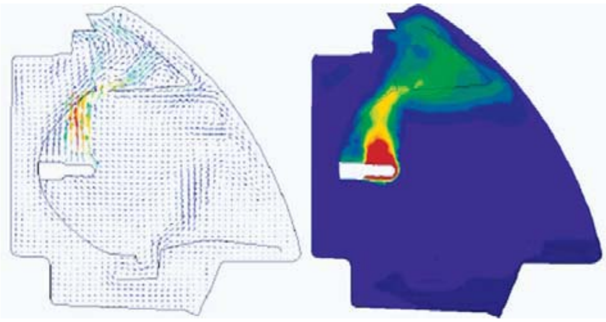


Fig. 3.38 Result of computational fluid dynamics compared to experimental results: air flow in the headlamp (left) temperature distribution in the headlamp (right)

Prediction of fogging and de-fogging by computational fluid dynamics

The prediction of the fogging and de-fogging behaviour of a headlamp or tail lamp is in principle, comparable to the weather forecast. From a theoretical point of view, a coupled problem must be solved, involving fluid dynamics and phase transitions. To this end, the headlamp or tail lamp chamber is discretised into volume elements, and equations of motion (moment balance) and heat transfer (energy balance, including radiation and convection) are being formulated. The influence of venting channels and other design details is taken into account by formulating the corresponding boundary conditions for the flow field. The equations are then solved numerically. The computational size and complexity of these problems is quite high and special algorithms have been developed for their solutions. Fig. 3.38 shows the result of a calculation compared to the experimental results.

Summary and Outlook

Fogging of headlamps and tail lamps is a common phenomenon. Simulations based on thermo-dynamical models of the system can be used in the design. Further developments of the underlying computational fluid dynamics codes and systematic validations based on experimental results can improve the quality of modelling.

There have been proposals to use anti-fog coatings i.e. hydrophilic layers on the inside of the outer lens to prevent the formation of water films. These materials have already been used in the past for the helmet shields of motorcyclists and in racing cars.

LED headlamps will have a completely different thermodynamic behaviour compared to present day headlamps. They will require special attention not only with respect to their fogging and de-fogging behaviour, but also to the limited maximum temperature of the light source.

Spotlight

Nanotechnology anti-fog coatings in automotive lighting and sensor applications

Introduction

The benefits of anti-fog coatings are avoiding visible condensation in headlamp lenses and optical sensors e.g. rear view cameras. This enables stable light and viewing efficiencies, hence conformity with safety aspects even under difficult ambient conditions. Headlamp systems which suffer from fogging do not provide the requested light intensity for a certain time. This effect is normally limited to a few minutes depending on several parameters, but it is certainly not in accordance with the state of the art with a view to achievable safety and decorative standards. With a view to AFS and LED application in headlamps, the relevance of anti-fog coatings will increase as first investigations have proved. Thus condensation will be a challenge in these lighting systems.

It should be noted that the respective nanotechnology anti-fog coatings cure under the same parameters as hard coats.

History

Automotive lighting has been subject to major changes during the last decade. Namely it has acquired more functions in view of design and safety aspects and is now approaching new technologies like Advanced Front Lighting (AFS) systems or the use of LED applications. These systems especially, require more attention in view to fogging as they will not heat up the cover lens as xenon or halogen light sources do.

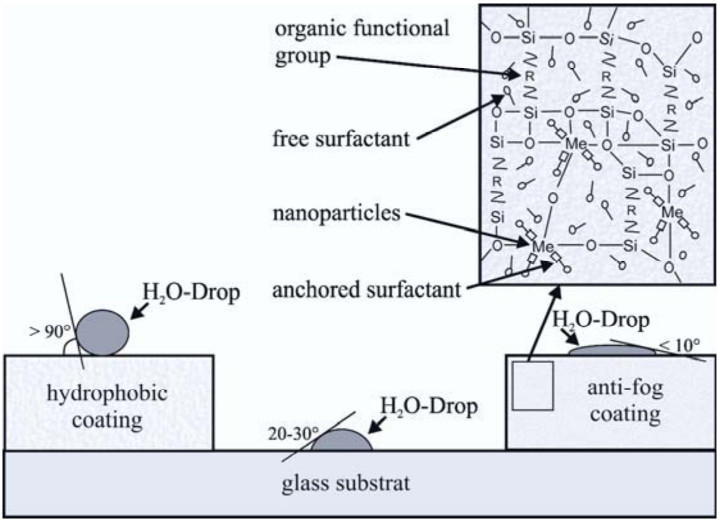


Fig. 3.39 Scheme of the anti-fog coatings

New solutions on different substrate materials are essentially required, reflecting a bundle of technical demands and follow the well-known basics like low costs, high reproducibility, reliability, and long-term stability. In this regard surface engineering and coating technology have gained more and more importance to upgrade systems, to bypass relevant problems or to expand material limits. This is demonstrated e.g. by the use of hard coatings for polycarbonate headlamp finishing. Self-cleaning or easy to clean functions, impact resistance, diffusion barriers on glass and plastics and anti-fog coatings are accessible by the use of the innovative combination of nanotechnology and sol-gel chemistry, in connection with approved and well-known series production technologies such as spraying.

Fogging and de-fogging behaviour can be approached by different simulation methods, but suffer in general from the lack of essential consideration of parameters like the surrounding vehicle and / or engine parameters (Maschkio 2004). Thus the problems occur during the first tests run on the completed car. Typical results can be seen in Fig. 3.35. It should be mentioned that fogging here does not refer to out-gassing (e.g. solvents coming from the different plastic components used), but to condensation of humidity inside headlamps and sensors.

This kind of condensation behaviour can be simulated in laboratory experiments. Subsequent photometric measurements prove that the oncoming traffic is glared significantly for a certain time, which depends on a diversity of parameters. Results with a H7 halogen lamp at GXC and an independent institute are shown in Table 3.3.

Table 3.3 Laboratory measurements of the glare light intensity with a view to fogging

	illuminance [lux] at glare point B50L, measured according to ECE directives	
status cover lens	without fogging	with fogging
non-coated lens	0.47	4.73
coated lens	0.47	0.47

In view of the "cold" LED-techniques used, the impact of fogging on the light efficiency and thus safety aspects on the street will increase. Measurements are ongoing and will be presented shortly.

State of the art of anti-fog coating

The most effective way to avoid fogging and related inconveniences is the use of an anti-fog coating. The mechanism of anti-fog coatings is mainly based on the following principles:

- The coatings' surface energy is higher than the surface tension of water,
- the coating is able to absorb water like a sponge,
- the coatings reduce the surface tension of water significantly.

Methods for the production of transparent and hydrophilic coatings are usually based on two principles:

- Use of organic polymers (e.g. polyurethane) with functional groups like COH, COOH which provided the high wet-ability towards water. These coatings have mainly been used on hydrophobic polymers.
- Integration of diffusible surfactants in the above mentioned materials for enhancing the hydrophilic effect.

In summary both systems delaminate, dissolve, or show limited transparency and / or limited water wet-ability in view to long-term stability. Thus the development of a superior system was focused on improving these properties, beginning with glass substrates. The developed coatings offer further potential for continuing improvements and adaptations with a view to performance, durability, and substrate material.

Chemistry of nanotechnology anti-fog coatings

The anti-fog treatment comprises a coating for glass or polycarbonate. This has a spontaneous water-spreading effect based on a hydrophilic inorganic-organic matrix, consisting of a nano-particle network supported by diffusible hydrophilic additives. This is schematically explained by Fig. 3.39.

The coatings consist of mixtures of:

- inorganic structures (0% to 90%)
- hydrophilic side chains (0% to 70%), e.g. polyether-, carboxylate- or phosphate-groups
- further organic side chains with special functional groups (0% to 50%), namely hydroxyl-, epoxy- or acryloxy-groups.

The synthesis generally starts with the production of nano-particles, which have to be stabilised in a solvent electro-statically or sterically. These nano-particular structures can be applied on surfaces using different methods such as flowing, dipping or spraying. The pH-value of the varnish can vary between 3 and 10 and the solid content is typically between 3 and 10 wt.%. The applied coating thickness is usually between 500 nm and 3 µm. The series products show coating thicknesses between 700 nm and 1 µm, ensuring a non-visible coating. As the demands on the lens quality in view to scratches, bubbles, inclusions and other cosmetic defects are very high, the coating quality has to follow these standards (PCT/DE).

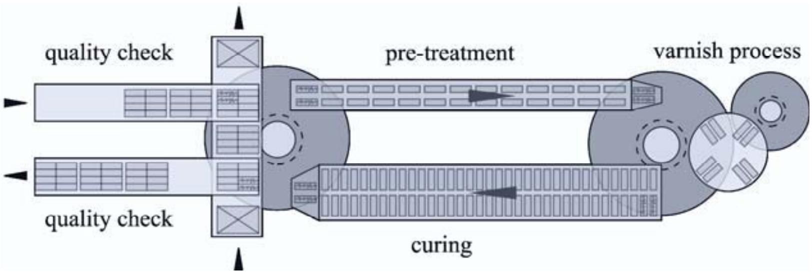


Fig. 3.40 Scheme of the automatic coating line

Series production of anti-fog coatings

The existing series production was preceded by an optimisation of the coating material and the substrate material in a batch mode in view of the demands of the automotive customers. The automatic coating line is state-of –

the-art, fulfilling the required technical and commercial objectives. Details can be taken from the scheme shown in Fig. 3.40.

The raw glasses are cleaned by a flaming process which is carried out by hand. Then they are checked carefully by eye following the customer's cosmetic criteria for the raw lens. After charging the substrates on the machine, a multi-step washing procedure follows which can operate with or without surfactants. Afterwards the lenses are dried by hot air. In a clean room, the lenses are given by a handling robot to a tool on a circulating table, with 4 positions for the varnishing process. The coating application itself is performed at position 2 of the table by a spraying robot considering the defined coating parameters. Thus thickness deviations are below 5% over the spraying area, which is checked by random testing of the finished product by an especially-adapted thickness measurement tool. The coated lenses are taken from the tool by the same handling robot and are given to the curing belt. There the coatings are hardened thermally using a temperature ramp. At the line-end the lenses are checked again visually and then packaged. This process has been adapted to polycarbonate substrates during 2004, concerning some details like the pre-treatment of the substrates. Furthermore the technical capability of the line was enhanced so that hard coats can be applied by spray coating too. This process offers a combined spraying of an anti-fog coating and a hard coat, which is done in a two-step spraying process in a clean room followed by the thermal curing of both coatings in parallel. In summary the process is characterised by

- high flexibility in view of coating material, substrate material and geometry and process parameters,
- low coating costs
- high reproducibility and low scrap rates

Coating properties and benefits

The anti-fog coatings on glass and polycarbonate show the following properties:

- Instantaneous anti-fog effect
- Contact angles towards water of 10° and lower, resulting in a spontaneous water-spreading effect
- Guaranteed function even with very thin coating (around 1 µm),
- Corresponding high surface energies
- Very good adhesion
- Excellent long-term stability of the hydrophilic effect
- High transparency

Typical test procedures of the automotive industry which are a vital part of a validation process and a production release are related to hydrothermal effects, because they are taken to extrapolate product life time.

The test methods should consider the intended use as a head- or a fog lamp and are under constant validation and improvement especially for new products like sensors.

The practical benefit is avoidance of fogging (droplets) of a transparent surface or component including the following advantages in view to automotive applications:

- Avoidance of an optical defect of today's mainly transparent automotive lenses ("technology to get your hands on")
- Creation of essential freedom for construction and design for the buying-decisive design of a headlamp ("face of the car", "seeing and being seen")
- Guarantee of stable light efficiency
- Avoiding of a burning glass effect
- Guarantee of functionality of driver assistance systems
- Conduction of the condensate possible

Conclusion

The technical and commercial feasibility of nanotechnology in combination with sol-gel chemistry, is proven with series production methods like spray coating in an automotive environment. The coatings on glass, PMMA, and polycarbonate are state-of-the-art. System upgrades are foreseen in close co-operation with the customers following their technical requirements. In detail, on glass this has to focus on further improvements of the heat resistance of the coatings (e.g. smaller and hotter fog lamps). Furthermore these systems have been adapted to other substrates like COC or SAN. Scratch resistance and 'Easy to clean' functions are also available by sol-gel chemistry and already on the market. The increased use of anti-fog coatings to other markets and the introduction of further products with customer-tailored functions and applications are ongoing. Driver assistance systems like reversing sensors, tracking sensors, and distance sensors have passed field tests and are being launched in 2006 with tailored functional transparent coatings. The described spraying process allows coating of both hard coat and anti-fog coat in one step without curing in between.

3.1.5 Day and night appearance

Design is increasingly determining the construction and configuration of headlamps. As the "eyes of the vehicle" they are an important stylistic element on the front of the vehicle, and accentuate the vehicle's character. The lighting systems used influence the effect of a headlamp, as do the shape and formation of the surrounding geometric shapes. The style of the light functions, such as position light and indicators, also offer potential to differentiate between brands. Quite apart from their appearance in daylight, the appearance of the headlamps at night in particular offers individual design possibilities.

Spotlight

Design appearance of headlamps

The car is more than a means to mobility. For many people it is also an expression of lifestyle, status and personal achievement. The car has prestige. It says something about its owner in the same way that clothes do. Headlamps play a significant part in automotive design and the communication of value for owner and driver. The headlamps are the 'eyes' of the car.

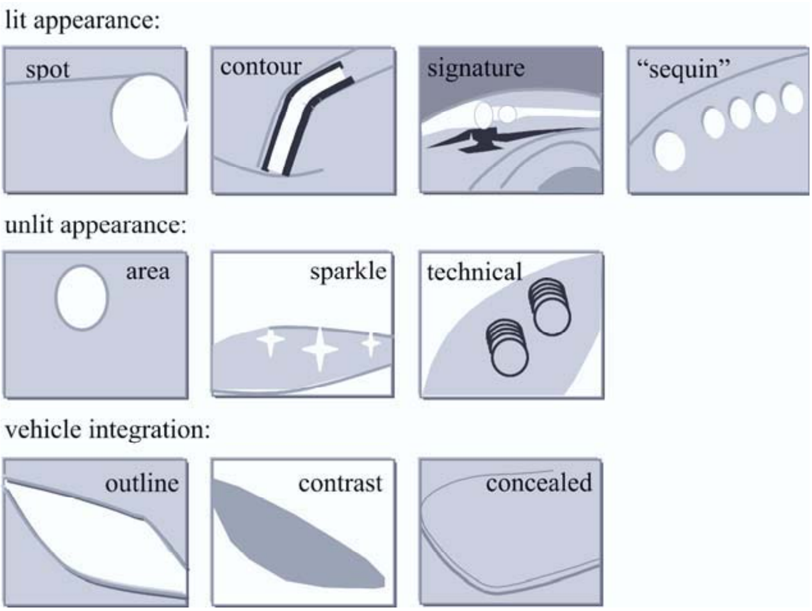


Fig. 3.41 Typical headlamp styles

The appearance of headlamps has changed over time. For instance in the 50's headlamps became an integral part of the car body. In the 70's they started to be aerodynamically styled and in the 90's the headlamps lens became clear, and allowed a more detailed look inside. At the turn of the millennium, aspects of night time styling and lit appearance became important. Previously these had only played a minor role. With the advent of adaptive front lighting systems, there is now a heightened interest in expressing the dynamic nature of headlamps by means of styling.

In the following section we illustrate current design trends with respect to unlit appearance, lit appearance and vehicle integration.

Show room - unlit appearance

Cars are still viewed, admired and bought with the lights off. Much to the dismay of the lighting engineer and designer, a prospective owner does not usually test-drive the headlamps or check whether the car looks good with the headlamps switched on. The unlit appearance of the headlamp counts towards the appreciation of a car. How much the headlamp helps to distinguish one vehicle from the other can be appreciated by just how many advertisements depict headlamps. Here is why:

- Sparkle – ever since free-form reflectors made the optical element on the headlamp lens obsolete, the stage has been clear for design aspects inside the headlamp. It became easy to give the headlamp a chrome look and make it sparkle.
- Technical look – without optical elements on the lens the headlamp could acquire further structure. Prominent projectors for dipped beam give the observer the feeling of powerful lights. If the projector lenses are surrounded by a black ring with the focal length imprinted, the look begins to resemble that of a camera lens, suggesting that lighting is not just powerful but also precise. Other styling means are used today to indicate the movement of dynamic lighting and engineering quality.

Night design - lit appearance

Cars used to be almost indistinguishable at night, when only the car lights provided a clue to their identity. This is beginning to change. More emphasis is now paid to night design. The following features are beginning to emerge and replace the amorphously lit spot common for a headlamp today:

- Contour and Signature – the contour of the headlamp is marked either by a precisely lit outline, or a specific light accenting a styling feature. For example light guides are used to mark styling lines. In some cases the light is deliberately made to illuminate parts of the car body, thus enhancing the vehicle’s appearance at night.
- Shaped spot or ‘Sequin?’ – The single spot of the headlamp is changed into a vehicle specific shape, or multiplied to create the effect of a set of pearls. With multiple projectors or in the future with LED headlamps, a row or array of lights can appear on the front of vehicles.

Vehicle integration – the eyes of the car?

It would be too simple to state that headlamps always have been and will be the ‘eyes’ of the car.

- Outline or contrast – the headlamp as the eye of the car can be accentuated further by simple means. The headlamp appearance can be lifted rather like make-up i.e. eye liner or eye shadow for human eyes. For example a line around the headlamp in a contrasting tone can provide a design accent just like eye liner. A lightly coloured headlamp lens or a toned bezel will mark the headlamp in the same way eye shadow emphasises eyes in a human face.
- Concealed - in some cultures the car is not viewed as having a face. For example in North America a car is often seen as related to a rocket or jet engine. The prominent feature on the front of cars in North America is the grill, to which the styling of the headlamps has to be subservient. In this case the hidden or concealed headlamp is attractive, and new solutions are beginning to emerge to replace the out-dated pop-up headlamp. Headlamp bezels for example in vehicle body colour are becoming more and more popular despite any logistical nightmare they may cause to the producers.

Fig. 3.42 Concealed headlamp using body colour bezel (source: Visteon)

Outlook

Vehicle design and styling will continue to change and evolve. The introduction of new technologies into lighting will create many challenges to marry appearance with functionality. The current trend to further vehicle differentiation, repeated face lifts and smaller production runs, will add to the design and engineering effort already posed by short development times.

3.1.6 Advanced front lighting

The primary aim of innovative headlamp systems is to increase traffic safety – especially at night. In order to achieve this in the future, optimum light distribution depending on driving and environmental conditions must be available to illuminate the road. Brightness conditions, weather, road conditions, the traffic situation, type of road, vehicle speed and acceleration behaviour will be taken into account by the AFS (Advanced Front lighting System) (Wördenweber, Lachmayer, Witt 1996).

Advanced front lighting systems have light distributions for a number of different, typical driving situations. The figure below shows the light distributions for advanced front lighting which include: Country Light, Motorway Light, Main beam, Front Fog Light, Adverse Weather Light, Town Light, Bending Light (shown here is only the static and not the dynamic bending light).

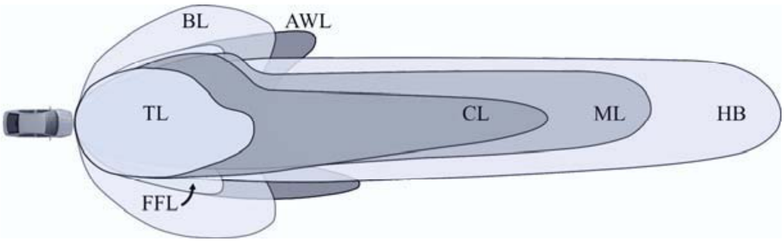


Fig. 3.43 Light distributions for advanced front lighting
CL – Country Light, ML – Motorway Light, HB – Main beam, FFL – Front Fog Light, AWL – Adverse Weather Light, TL – Town Light, BL – Bending Light

A typical characteristic of town light distribution is the wide illumination of the road, the reduced asymmetric sector to prevent dazzling other road users, and the good illumination of the area directly in front of the vehicle. When driving around bends it is appropriate to let today's dipped beam pattern follow the course of the road dynamically. When turning corners, today's dipped beam is supplemented by an additional light sector (static curve light), to better illuminate the adjoining road. For motorway lighting the raised symmetrical cut-off leads to a clearly larger range of vision, without however, dazzling oncoming traffic. In addition an adverse weather light is under discussion, which should lead to more safety, especially in rain and wet road conditions.

Spotlight

Advanced front lighting – Concept overview

Introduction

This spotlight is about a new forward lighting system, which offers a big step forward in automotive technology. It benefits drivers and will help to improve safety on the roads at night. It should be noted that the ECE regulations referred to in the spotlight are nearly, but not yet finally approved by the Economic Council of Europe at the time of print. At present the proposal for the AFS system is waiting for approval in the working group WP29.

Adaptive front lighting systems (AFS) are lighting devices which automatically adapt the beam characteristics of the dipped and main beam to a number of different conditions. The systems consist of a system control, one or more supply and operating devices and the installation units on the left and right side of the vehicle. AFS introduces new classes of light distributions. These are:

- Class C (Basic) dipped beam
- Class V (Town) dipped beam
- Class E (Motorway) dipped beam
- Class W (Wet road) dipped beam

All functions can operate in different modes. In particular, the AFS regulation defines Mode T (bending mode) for which two categories exit:

- category 1 – Dynamic
- category 2 – Static

The systems can be equipped with halogen light sources according to regulation ECE 37, or xenon light sources according to regulation ECE 99, or with non-replaceable light sources.

The advantages of AFS in comparison to conventional headlamp systems are as follows:

- Adaptive light distributions: a number of different light distributions beyond dipped and main beam will create the right light for a number of different situations, such as motorway driving, town driving or driving in adverse weather. The change between modes and classes will be continuous (see below).
- Design freedom: new technologies will be able to be used as a number of current restrictions are lifted. For example more than one light source can be used to increase the performance of the so-called dipped beam. AFS units can be situated on the car non-symmetrically, that is the left and the right side of the car headlamp may be different. Moreover, the appearance of each headlamp (inner building) can be different too.

- Systems will be equipped with headlamp cleaner and automatic levelling system (regardless of used light source).

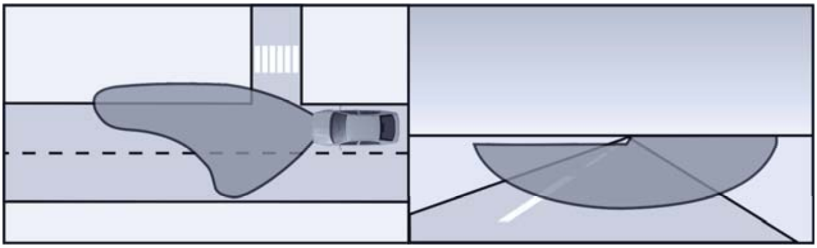


Fig. 3.44 Birds-eye view of class C (basic) dipped beam (left); driver's view of class C (basic) dipped beam

Class C (Basic) dipped beam

The basic dipped beam can be created with either halogen or xenon light sources and it can be created by more than one light source. The lighting performance is 100%.

Class V (Town) dipped beam

The town dipped beam is suitable for illuminating the road in towns. The beam has a wider horizontal range for better visibility of pedestrians, road markings, signs and crossroads. It is activated at speeds below 50 km/h or if the luminance of the road surface is higher than 1 cd/m^2. The lighting performance is set to 50%.

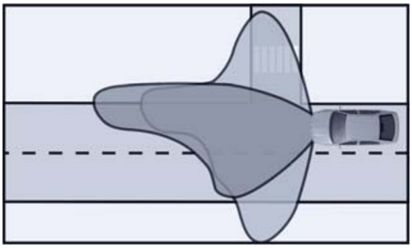


Fig. 3.45 Birds-eye view of class V (town) dipped beam. Light yellow area indicates beam extension to the side for better illumination of pedestrians, road markings and signs.

Class E (Motorway) dipped beam

When the vehicle is moving at speeds over 110 km/h, or the road characteristics correspond to motorway conditions, the basic dipped beam is automatically moved up 0.25° to extend the range of light in the front of the vehicle. Lighting performance is set to 100%.

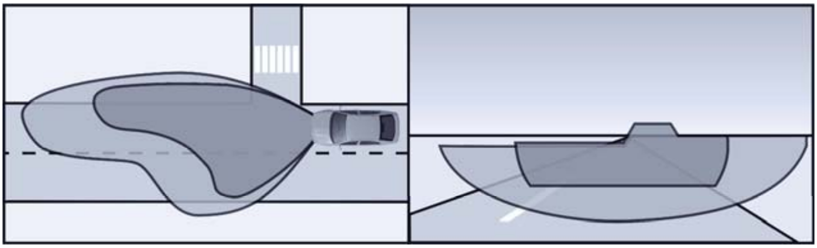


Fig. 3.46 Birds-eye view for class E (motorway) dipped beam (left); driver's view of class E (motorway) dipped beam. The light yellow area indicates the raised beam (0.25°) for extended range

Class W (Wet road) dipped beam

After the detection of rain or water on the road, or if the windscreen wiper is switched on, the basic class is changed to "wet road". The illumination of the road just in front of the vehicle is reduced to prevent glare and there is increased light for the side of the road. Lighting performance is set to 100%.

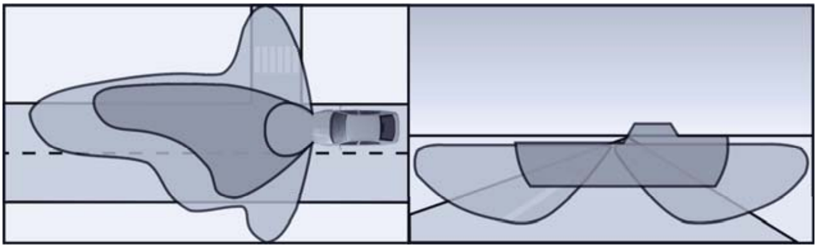


Fig. 3.47 Birds-eye view for Class W (wet road) dipped beam. Light yellow area indicates better illumination of verges and a reduction of illumination just in front of the vehicle.

Bending modes T

All classes (C, V, E and W) can be modified to become a bending mode. The whole beam, or parts of it, can swivel into the bend.

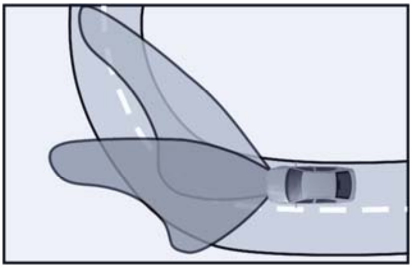


Fig. 3.48 Birds-eye view for class T (town) dipped beam. This is an example of dynamic bending mode, where the whole beam is swivelled to the side

In static bending mode an additional light is turned on in the headlamp, when the vehicle is moving into the curve. This additional light source must be an integral part of the headlamp.

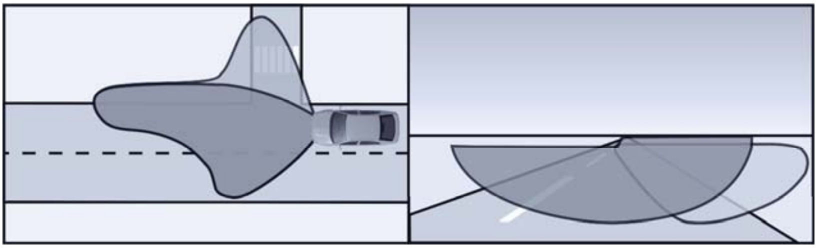


Fig. 3.49 Birds-eye view for class T (town) dipped beam. This is an example of static bending mode. Activated additional light source (static mode) increases the side illumination (light yellow area) and illuminates the direction of the curve.

Measuring AFS front lighting systems

For AFS systems the same set-up is used as for standard ECE headlamps. Measuring points are defined on a wall 25 m in front of the car. Maximum or minimum illuminance values are defined for each of the points (see Fig. 3.50). The headlamps are aimed in accordance with the class of the light distribution i.e. for basic 0.57°, for town 1.3° and for motorway 0.23° below the horizontal line. Bending modes are measured in the neutral positions and in extreme positions to the side (dynamic bending), or with additional sources switched on (static bending). For xenon light sources measured values are multiplied by 0.7.

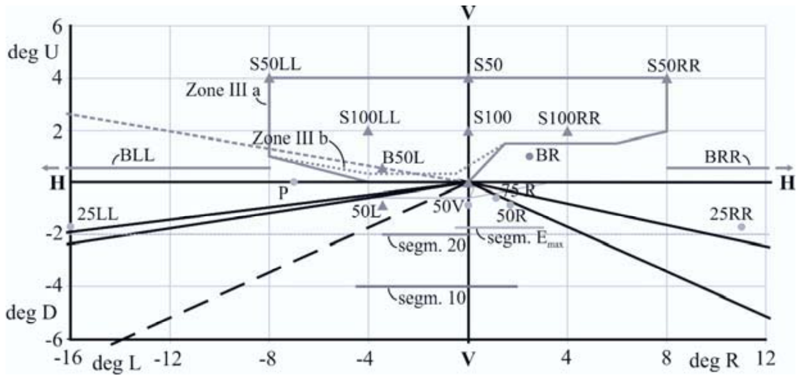


Fig. 3.50 Schema of measuring points, segments and zone on the ECE testing wall. For right hand drive traffic the table is flipped over left to right.

Fail-safe provisions for AFS

In the case of a malfunction of the AFS, an automatic fail-safe mode is required. The tell-tale control light must be on and the light beam must be aimed, so that in any position it shows at most 2 lx above the horizontal cut-off line. Moreover, at specific points (50 V and 25RR/25LL) the minimal light intensity must be 3 lx and 0.5 lx respectively.

Type-approval

For type-approval of such systems a comprehensive test is necessary. It is necessary to provide all technical documentation (drawings, description), samples and an electronic control box which substitutes the electronic environment in the car. Additionally there must be a documented “safety concept”, which describes fail-safe features.

Each AFS function (class, mode) must be approved and will have its own approval mark, which is shown on the headlamp lens:

- X - AFS
- C - Class C (basic)
- V - Class V (town)
- E - Class E (motorway)
- W - Class W (wet road)
- T - Bending mode

The following figure illustrates the marking for an AFS type headlamp with:

- 02 A front position lamp
- 00 X CTV R AFS with basic, town, bending mode and main beam
- 00 RL daytime running lamp

- 01 1a front turn indicator of category 1a

Fig. 3.51 Example of AFS approval markings

Installation (ECE AFS R48)

The ECE AFS R48 regulation describes the requirements for the assembly of lighting systems on motor vehicles. Note: the nature of AFS allows the lighting units to be asymmetric.

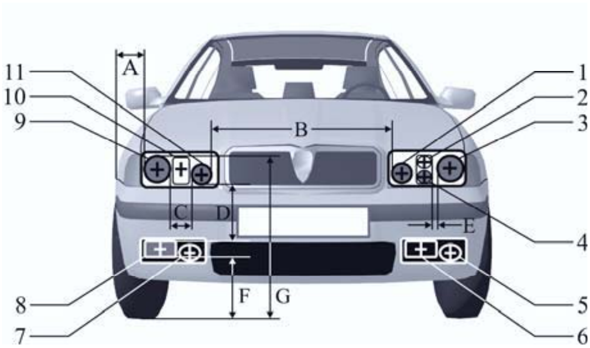


Fig. 3.52 Front lighting installation as defined by the ECE AFS regulation

Lighting units switched on simultaneously for a given lighting mode:
- No. 3 and 9: two symmetrically placed lighting units
- No. 1 and 11: two symmetrically placed lighting units
- No. 4 and 8: two additional lighting units

Lighting units not switched on for said lighting mode:
- No. 2 and 10: two symmetrically placed lighting units
- No. 5: additional lighting unit
- No. 6 and 7: two symmetrically placed lighting units

Dimensional measurements are limited as follows:
- $A \leq 400$ mm
- $B \geq 600$ mm, or ≥ 400 mm if vehicle overall width < 1300 mm
- $C \leq 200$, $E \leq 140$
- $D \leq 400$, $F \geq 250$, $G \leq 1200$

Outlook

The regulations for AFS represent a giant leap into a new generation of forward lighting systems. Before AFS, vehicle lighting was defined by the component (e.g. headlamp or fog lamp) and its characteristics, such as approved light sources or installation. With AFS complex functions are defined which no longer match the components one by one. This carries with it far reaching implications for type approval, compliance testing and operational check. For example, it will not necessarily be easy to tell by just looking at the headlamps, whether the lights are working properly or not.

3.1.7 Night vision systems

Night-Vision Systems are being offered as an option for some vehicles. The camera can provides the driver with an artificial eye, showing objects within the driver's visual field which otherwise may remain invisible with just normal headlamp light Despite oncoming traffic a pedestrian is clearly visible at a distance of about 60 m. This is not possible with the unassisted eye because everything above knee-height is not illuminated by dipped beam of the headlamp. The night-vision systems use infrared light, which is invisible to the human eye. Recognised objects can be visualised on a monitor or via a reflection in the windscreen using a head-up display.

Spotlight

Automotive night vision systems

When considering night vision systems it is important to bear in mind what they can and cannot do. Night vision systems offer a limited field of view. It is always preferable to use high beam illumination and normal vision. Only in situations where the high beam cannot be used at night, can a night vision system assist the driver in checking the situation for potential dangers. The driver should consult the night vision display only when he has the feeling that he does not have enough information. An extensive study of general aspects of night vision systems has been performed by the University of Michigan Transportation Research Institute.

Different technical implementations of night vision systems are available. The main distinction is between active systems, which rely on near infra-red radiation, and passive systems, which detect body heat i.e. far infra-red radiation.

Passive night vision systems have no infrared illuminator. They rely on detection of thermal radiation in the range of 8 µm – 14 µm or on image intensification. Both originate from military systems (“see without being seen”).

A distinct feature of thermal systems is the ability to differentiate warm objects (pedestrians, animals) from a cold background. Therefore they lend themselves to object recognition systems. Important disadvantages are that they do not show objects against a background of the same temperature (lane markings, stones in the road), they show poor contrast if the background is above 25°C and the images are often not intuitively understood (the hot exhaust show up very bright). To the untrained eye the images appear more like a photo negative. A number of thermal systems have been on the market since 1998 (Raytheon camera in Cadillac DeVille).

Image intensification uses special components (I-CCDs) to intensify weak ambient light. As they are very sensitive to glare from any light sources, they are not well suited for automotive applications.

Active night vision systems

Active systems use a near infrared radiation (NIR) source in the range 780 nm – 1000 nm. This wavelength range can be detected by a charge-coupled device (CCD) or complementary metal-oxide semiconductor (CMOS) cameras. As the NIR radiation is close to the visible wavelength range, reflectance of most objects is similar and images are easy to understand. Additionally, many fabrics which appear black to the eye have high NIR reflection. Road markings, road signs and stray objects can easily be recognised in the image. The first active system was introduced into the market by Toyota in 2002.

In this spotlight the active night vision systems will be discussed in greater depth.

Infra-red sources and the relationship to cameras

Both incandescent and luminescent sources can be used to generate near infrared radiation. The spectral distribution of the radiation source has to match with the spectral sensitivity of the camera. But that is not all. Additional care has to be taken with respect to eye safety and the potentially appearance of red light at the front of the vehicle.

- Eye safety:
  The human eye is naturally exposed to infra-red radiation, but always in combination with either bright light or strong heat. If the eye is exposed only to radiation in the range beyond 780 nm, the natural protection, such as eye-lid or pupil reflexes will not be triggered. This is could be critical for eye safety.

- Latent red effect:

  The spectral sensitivity of the human eye is defined by the V(λ)-curve. At 780 nm, the relative spectral sensitivity is 1/100.000 of the maximum (at 555 nm). However, the human eye is still sensitive at these wavelengths and translates them into a deep red. Therefore special care has to be taken to avoid a red light at the front of the vehicle.

The simplest solution is to use a high beam with a halogen light source modified with a colour filter with edge characteristic (e.g. RG780). With a 3000°K filament temperature the maximum of the emission is at a wavelength of 970nm. This however, creates a problem for the camera as the spectral sensitivity of a silicon chip drops linearly to zero between 780 nm and 1000 nm, i.e. most of the IR radiation from an incandescent source is not detected.

Another possible source of infra-red radiation is the high-intensity discharge source, known also as HID or xenon. The xenon spectrum contains a strong emission line around 810 nm. This would be very well suited for an IR illumination. In principle it should even be possible to balance VIS and IR emission with suitable metal vapours. The current market penetration of night vision systems however, means this option is not economically viable.

A third option is the infra-red diode (IRED). As the emission is concentrated close to the maximum sensitivity of the camera chip, the same integrated IR power from a semiconductor source yields approximately twice the photocurrent as from an incandescent source. Eye safety is less of a concern, as the semiconductor emits no radiation between 1050 nm – 1400 nm. Consequently, a solid state IR source system has a higher efficiency compared to an incandescent system. This can be used to increase the reach of the system or to reduce costs.

Fig. 3.53 : Night vision image from DaimlerChrysler experimental laser/CCD system (source: DaimlerChrysler)

Technically however, laser diodes are the first choice. They have the highest possible radiance, high efficiency, high power per component (≈2 W, where IREDs achieve ≈50 mW), small spectral bandwidth (smaller by a factor of 10 than IREDs), a radiation pattern which is close to the required radiation pattern for a night vision system (compared to the approximately Lambertian radiation pattern of IREDs), and require only a small optical window at the front of the car. If the cost of the laser diode and the thermoelectric coolers (note: the wavelength of the laser shifts 0.3 nm per degree operating temperature) becomes competitive, it is certain that it will replace both IRED and eventually the incandescent source for infra-red radiation.

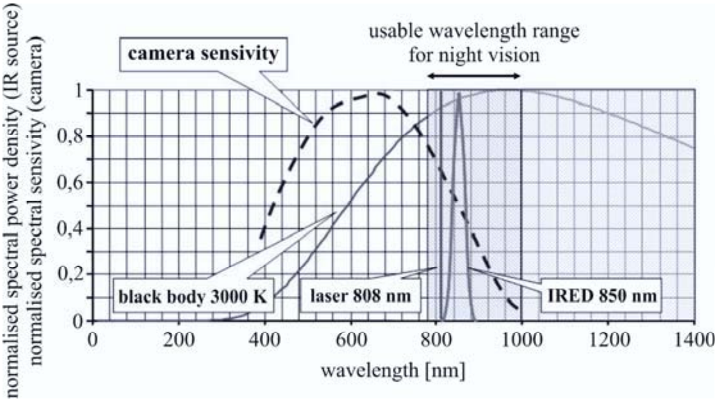


Fig. 3.54 Normalised spectral emission and camera sensitivity. Note that the spectral sensitivity between CCD and CMOS and between suppliers/models can vary (source: DaimlerChrysler)

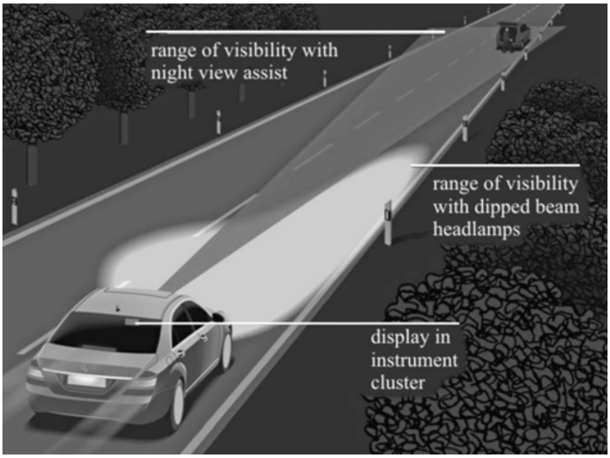


Fig. 3.55 Comparison between the ranges of low beam and night view assist infrared (source: DaimlerChrysler)

The Mercedes S-Class described in more detail below, uses a halogen light source with an edge filter to create an infra-red high beam with a narrow frequency range. It utilises a CMOS-camera with high sensitivity and high dynamic range in order to cope with glare light from oncoming traffic.

DaimlerChrysler's realisation of a night vision system

In September 2005 DaimlerChrysler introduced an active night vision system and named it 'Night View Assist'. When high beams cannot be used at night, the system enables the driver to see further than with just the dipped beam. Thus pedestrians, cyclists and obstacles can be recognised sooner. Additionally, the driver will have a better vision of the course of the road.

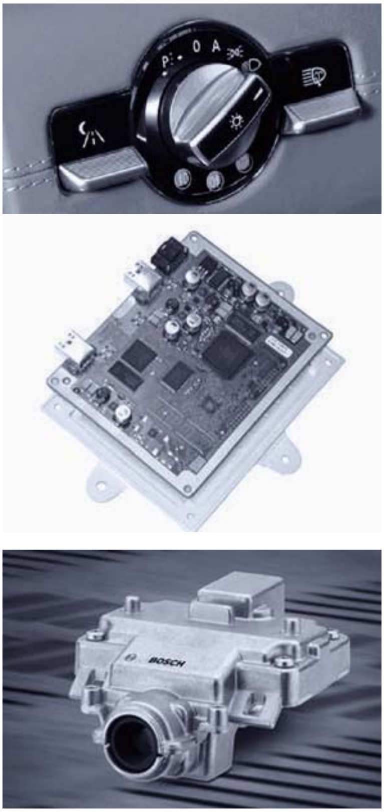


Fig. 3.56 Rotary light switch with button for the night view assist (top), control unit (middle), camera of the night view assist (bottom) (source: DaimlerChrysler)

The Night View Assist mainly consists of the following components:

- The driver activates the system by means of a switch to the left of the rotary light switch.
- Two special beams in the headlamp illuminate the road ahead with invisible infrared. When Night View Assist is active, these are automatically switched on at speeds above 15 kph, and when braking remain active down to 10 kph.
- An infrared-sensitive camera inside the windscreen within the wiping area of the windscreen wiper, records the scene ahead of the vehicle. A diffused-light panel protects the camera against extraneous light reflections.
- An electronic control unit processes the image from the camera and transfers it to the eight-inch black and white display in the instrument cluster which is in the driver's direct field of vision.

Fig. 3.57 Comparison without (top) and with night view assist (bottom) (source: DaimlerChrysler)

Night View Assist has the same range as main-beam headlamps, but without dazzling the oncoming cars. Even when the headlamps of oncoming vehicles blind the driver and heavily obscure the view, visibility is much better with this support system: a test dummy in light-coloured clothing standing at the road edge 50 m behind an oncoming vehicle, was detected from an average distance of 140 m with the help of Night View Assist – around 53 m sooner than with dipped beam alone.

3.2 Rear and signal lights

The traffic scene in Fig. 3.58 raises further questions, the most important of which will be the subject of this section: which signals are there and what purpose should they serve? Vehicles with faulty lights distract drivers again and again in road traffic. Which technologies and bulbs are being used today and will be used in the future? Why is it still a challenge to develop and manufacture lamps for vehicles?

Fig. 3.58 Rear view of two vehicles ahead in clear view (top), mild fog (middle) and heavy fog (bottom)

Signals from different vehicles can often be recognised with varying degrees of clarity. Sometimes they are an identification feature of the vehicle itself. New technologies offer possibilities for signal language using form and colour. The following paragraphs give an overview of current technologies for signal lights, illustrate the relevance for safety and show the need for people-friendly information in traffic.

3.2.1 Installation and functions

Decisive for road traffic safety is the ability to recognise reliably a driving situation. Signal lamps – whether they are at the front, side or on the rear of the vehicle – pass on information to other road users. Predominantly the following signals are in use.

To the rear the following signals are usually incorporated into one or two tail lamps:

- The tail function, sometimes referred to as rear position lamp (RPO), marks the vehicle position in traffic particularly in twilight (low contrast!) and darkness.
- The stop (SL) or brake light signals to the following traffic that the vehicle in front is reducing speed or standing still.
- The rear turn indicator, also referred to as direction indicator (DI), warns the following traffic of the intention to change direction or lane.
- The rear fog lamp (RF) marks the position of the vehicle in dense fog, falling snow, hard rain or dust. In many countries the use of the fog lamp is limited to situations where vision is reduced to 50 metres or less. The fog lamp is optional for SAE compliant tail lamps.
- The reversing light (RL) shows that the vehicle is intending to or is already driving backwards. The operation of the reversing light is coupled with the selection of reverse gear.
- The central high mount stop lamp (CHMSL) is an additional brake lamp mounted centrally on the vehicle in a raised position. As the brake lights of the vehicle two ahead may be obscured by the preceding vehicle, the central high mount stop lamp tends to be more conspicuous, as it is generally visible through the car ahead.
- The licence plate is lit with either one or two lamps.
- The rear reflex (RR) is not a lamp, but a reflex reflector. It returns the light of a light source, such as the headlamps of a following vehicle. The reflex is sometimes referred to as a passive lighting function.

To the side a vehicle typically shows the following signals:

- The side turn indicator (side DI) is mandatory for ECE approved vehicles and repeats the signal of the turn indicator to the side.
- The side marker lamp (SML) and the side reflex are mandatory for SAE approved vehicles and for all lorries. Reflex reflector and lamp are often integrated into one device.

To the front, the following signals are often integrated into the headlamp:

- The front turn or direction indicator (FDI) signals the intention to change direction or lane. Depending on the distance to the dipped beam or fog beam the intensity required for the turn indicator differs.
- The position lamp (PO) signals the position and width of the vehicle and is often integrated directly either into the main beam or dipped beam reflector. Note- the position lamp is also used to mark a vehicle when it is parked in unlit areas.
- The day time running light (DRL) marks the vehicle when operated during the day. In many countries, most notably countries with extended periods of low contrast such as Canada or the Scandinavian countries, the use of day time running lights is mandatory. The day time running light can be realised either by means of a separate lamp, by dipped beam or by a dimmed main beam.

Fig. 3.59 Separate day time running light (right) with white LEDs (source: Audi)

The signals show whether the vehicle is on the road and what position it is in (DRL, PO, SML, RPO, RF, RR, SMR), whether it is stopping (SL, CHMSL), changing direction (front, rear and side DI) or reversing (RL).

In order to guarantee recognition and remove ambiguity, the signal functions on the vehicle differ in their level of luminous intensity, their relative distribution of luminous intensity, their colour and sometimes also their frequency.

For reasons of uniformity of the signal image, vehicle signal lights are governed by legal regulations. The level of permissible luminous intensity values differs depending on the function. Generally, changes in movement (DI, SL) are indicated by a stronger signal than position and orientation (RPO, PO and SML).

It should be noted that there are separate requirement for

- lamps for lorries and trailers which additionally have front position lights, end contour marker lamps and lamps for elevating gates
- special lamps for vehicles belonging to the emergency services, like rotating beacon, flashing lights, indicator lamps and warning lamps
- bicycle lamps including headlamps, tail light and front, side and rear reflex reflectors
- lamps for sport boats such as position lanterns, rear lanterns, top lanterns, anchor lanterns and
- lamps for aircraft which comprise landing lights, tail navigation lights, wing navigation lights, anti collision strobe lights and airport ground operation lights

3.2.2 Design concepts

Nearly one seventh of all road users' drives with faulty lighting equipment. The predominant reason for this is long usage times for lights. For a vehicle life of 150,000 km the duty cycle predicts about 1500 h of usage for the dipped beam, about 100 h for the turn indicator, an average of 600 h for the brake light and a maximum of 30 h for reverse.

For example, a double filament standard bulb with an electric power consumption of 21 and 5 Watts for a combined stop/tail light function has a service life of approx. 100 h (stop) and 1500 h (tail). Taking an average service life of 540 h, the lamp for the stop light must statistically be replaced 5 times. If the vehicle is mainly driven at night, which is especially true in the case of the Nordic countries, or for taxis and lorries, the number of bulb replacements rises to 18. The use of long life bulbs reduces the service frequency of the same functions by about half. When light emitting diodes with an average service life of more than 10,000 h are used, there is no longer any need to replace the light source.

Semiconductor light sources also offer more advantages than bulbs with regard to energy consumption. If the tail light function for example, is performed by 4 red light emitting diodes rather than two 5-Watt bulbs, the power consumption is reduced by about a factor of 17 from 10 W to 600 mW.

The choice of bulb is only one of the constructional parameters. In addition, the framework within which lamps are developed is defined by: the technical requirements for the various signal functions as prescribed by regulations; the customer's specific requirements regarding mechanical strength, air-tightness, resistance to surrounding pollution etc.; the customer's specific demands on styling requirements; and the materials available.

A conventional car signal lamp consists essentially of three assembly groups: the bulb holder positions one or more light sources relative to the optical system of the lamp; the housing contains the reflectors which are generally moulded in one, and the cover lens is usually responsible for the distribution of the light, thanks to its additional optical structures. Modern structural shapes of lamps sometimes put other concepts into practice and then integrate corresponding optical components such as reflector optics, intermediate lenses or light guides.

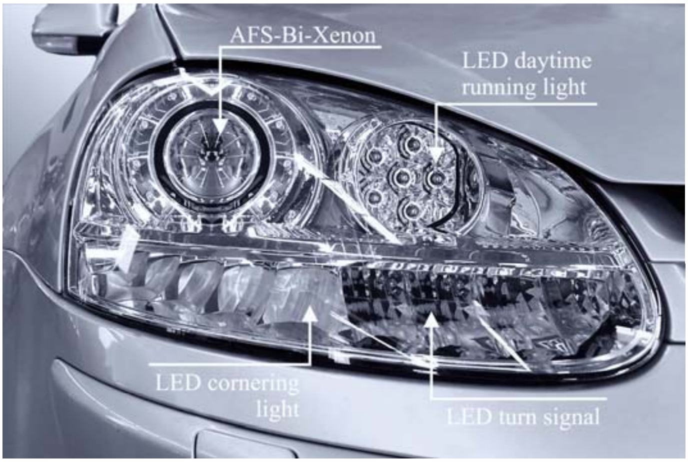


Fig. 3.60 Turn signal with LEDs and free-form reflector (bottom right) (source: Visteon)

3.2.3 Optical concepts

Apart from the demand for new types of styling, the increased use of alternative light sources such as new bulbs, LED or laser in car lamps makes the development of innovative and highly efficient systems necessary.

Through the use of different types of optical components these lamps then also become differentiated in appearance and in packaging. Independently of the choice of bulbs, the different optical systems can be roughly classified as follows.

Reflective optics

Lamps with purely reflective properties typically consist of free-form reflectors combined with pattern-free cover lenses.

Most lamps used at the moment are made up of so-called mixed- or hybrid optics, most of which use reflective elements combined with other optical (e.g. light guide or refracting) principles.

Examples of the most usual reflector forms in a lamp are: parabolic reflector, ellipsoidal reflector, stepped reflector, free-form reflector, segmented or facetted reflectors and a combination of the reflector geometries mentioned above.

Refractive optics

Lighting systems which predominantly use refractive elements are for example, tail lights or indicator lights. Typically, Fresnel optics are used on curved surfaces in the intermediate or cover lens. These systems manage without additional reflectors.

Light- guide optics

For lamps using light guide technology, the difference must first be made between pure light guiding and the out-coupling of light. Light guiding is based on total reflection occurring at the transition interface between the optically thicker and the optically thinner medium. The limiting angle up to which light guiding is possible is determined by the difference between the refractive indices of both materials. If beams meet the interface at a steeper angle they are out-coupled. Mirror prisms are fitted for example, for directed out-coupling in or on the light guide. This principle is used in the production of lamps.

Spotlight

Light guides for automotive application

Light guides offer great opportunities to design attractive exterior lamps, e.g. front position lights, tail lamps or side lights. Light guides are used for signature lighting in order to highlight important styling lines, contours around lighting chambers or the edges of a lamp. Furthermore they play an important role in ambient interior lighting.

History

The history of dielectric optical light guides goes back to Victorian times, when the total internal reflection principle was used to illuminate streams of water in elaborate public fountains. Later developments led to the use of light guides in cars, where light guides create important design elements in automotive exterior or interior lighting.

Application

Rays in a light guide continue to be reflected internally. Light from the light source is coupled into an entrance surface of the light guide made of transparent material and it is guided through the light guide by TIR. The refractive index of the surrounding material must be lower than the refractive index of the light guide material. In the case of the automotive application the surrounding material is typically air.

To decouple light from the light guide a prismatic structure is used. The condition of TIR is broken for light rays that reach the prismatic structure and these rays leave the light guide in the direction set by the prismatic structure (see figure below).

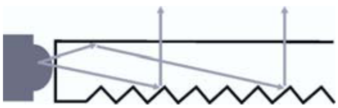


Fig. 3.61 Light Guide using LED as a light source

Of the typical light sources for automotive lighting, LEDs are the preferred sources for light guides. Due to their low heat emission and small dimensions, it is possible to place LEDs very close to the plastic light guide and achieve efficient light coupling. Depending on the radiation pattern of the LED used, the light can either be coupled directly into the light guide or collimated by the input surface of the light guide. The direct coupling is applicable when LEDs with a narrow radiation pattern are used. Collimating is required for LEDs with a wide radiation pattern.

Fig. 3.62 Example of light coupling from LEDs

Incandescent bulbs can also be used for light guides. Due to the high infra-red content and the radiation pattern of bulbs, it is not possible to couple their light directly into the light guide. The filament of the bulb is an isotropic light source and the solid angle of entrance at the surface of the light guide is less than 1°, depending on the diameter of the light guide and the distance of the light guide from the bulb. Thus the efficiency of direct in-coupling of light from the bulb is very low. To achieve sufficient efficiency, the light from a bulb can be focused using an elliptical reflector. In the case of a plastic light guide the IR part of the light must be reduced by a heat-protection filter.

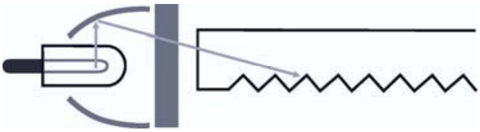


Fig. 3.63 Example of light coupling from an incandescent bulb

An important parameter of the light guide is its uniform lit appearance. Light uniformity is influenced by many parameters e.g. the radiation pattern of the light source used, the geometry of the prismatic structure, the material used or the scattering losses of light etc.

The acceptance angle of an individual prism changes with its distance from the source. Combined with the radiation pattern of the source, this usually leads to an exponential decrease of the light flux inside the light guide. This situation is shown in the following figures (Fig. 3.64, Fig. 3.65, Fig. 3.66).

The shape of the prismatic structure influences the direction of the de-coupled rays from the light guide and tailors the spreading of the light beam. Fig. 3.66 shows an example of a typical prismatic element.

The direction of the de-coupled rays from the light guide and the efficiency of the reflection on each prism are given by the angle β [rad] between the input surface of the prism and the wall of the light guide. The angle β is approximated using the following equation:

$$\beta = \frac{\frac{\pi}{2} - \mathrm{arctg}\left(\frac{D/2 - V}{vzd}\right)}{2} \tag{1}$$

…where D is the diameter of the light guide, V is the depth of the prism and vzd is the distance of the prism from the entrance surface of the light guide.

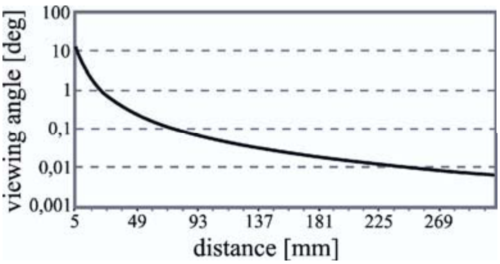


Fig. 3.64 Dependence of viewing angle on the distance along the light guide

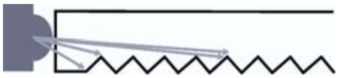


Fig. 3.65 Dependence of viewing angle on the distance along the light guide

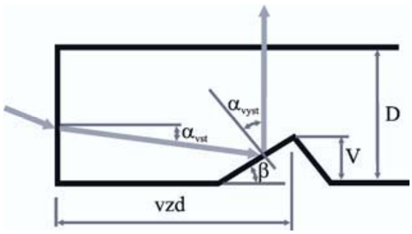


Fig. 3.66 The shape of a typical prismatic element

The formula (1) provides good results for direct light from a light source especially at the beginning of the light guide. In the centre of the light guide it is more beneficial to use a formula that considers one reflection on the sidewall of the light guide:

$$\beta = \frac{\frac{\pi}{2} - \mathrm{arctg}\left(\frac{D/2 - V + D}{vzd}\right)}{2} \qquad (2)$$

The efficiency of the reflection on each prism depends on the incidence angleβ, given by the Fresnel coefficient (Born and Wolf 1999). The efficiency continuously increases with the distance from the entrance surface of the light guide to 100% - TIR (see figures below).

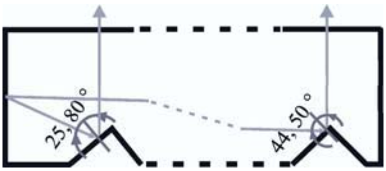


Fig. 3.67 Different incident angles at the beginning and end of the light guide

TIR occurs if the incident angle is bigger than the critical angle $\beta_{c.}$ From Snell's law for the critical angle we obtain formula:

$$\sin \beta_c = \frac{1}{n} \qquad (3)$$

For example, for clear polymethacrylate (PMMA) with a refractive index of n = 1.493, the value of the critical angle is 42°.

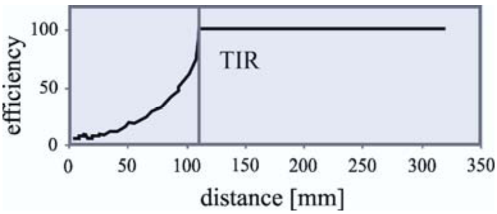


Fig. 3.68 Efficiency of light reflection by the prismatic structure

Although the first few elements receive much more energy directly from the light source, the efficiency of the reflection is lower than in the middle of the light guide, where the prism elements are calculated assuming one reflection along the length of the light guide. The light uniformity can be further improved by shaping the prismatic structure.

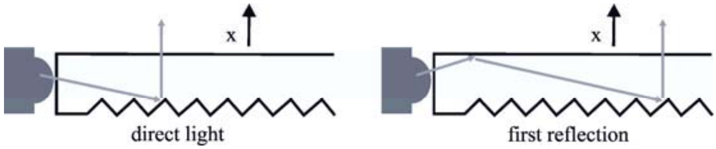


Fig. 3.69 Direct and reflected light

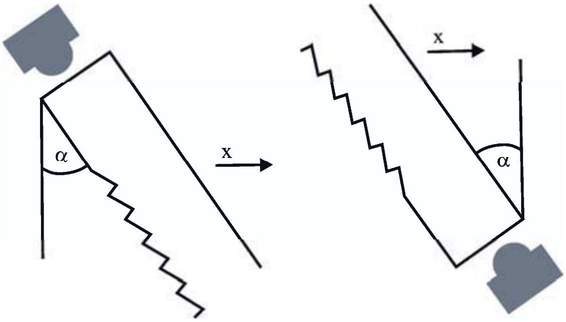


Fig. 3.70 Inclined light guide. Left: TIR, Right: Fresnel reflection

The previous formulae are derived for light guides placed in the normal plane or close to normal to the decoupling direction. For the inclined light guide the value of β depends on the overall inclination angle α (see Fig. 3.70).

The position of the light source is very important for inclined light guides and significantly influences the efficiency of the whole optical system. Fig. 3.70 shows two possible situations for identical light guides. In the case of the light guide shown on the left the rays reach the prismatic structure at an angle greater than 42°. Hence the condition for TIR is fulfilled and the system efficiency is good. In the case of the light guide in Fig. 3.70 on the right, only Fresnel reflection occurs and the efficiency of the optical system is poor. In the case of bent light guides, each prism element has to be computed separately.

Some examples of using a light guide in a front or tail lamp

Light guides can be used to illuminate very long and thin areas in lamps. The photos show the unlit and the lit appearance of such a lamp. Two light guides are each fed by LEDs with a narrow radiation pattern.

Fig. 3.71 Example of a light guide as a front position light. The light guide highlights the bottom edge of the headlamp. It creates a stylistic feature that totally changes the appearance of the headlamp. Two white LEDs with Lambertian characteristics feed the light guide (source: Visteon)

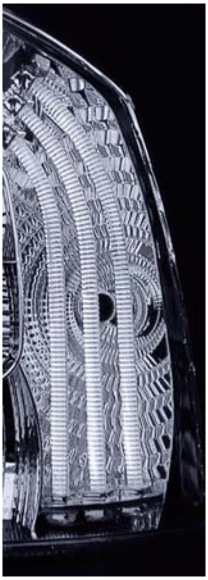


Fig. 3.72 This example shows light guides that highlight the outside edge of the rear lamp and function as a position light. Six LEDs with narrow radiation pattern feed three light guides from both ends (source: Visteon)

Fig. 3.73 Example for light guides in very long and thin areas (source: Visteon)

Outlook

The utilisation of light guides in automotive applications followed a distinct pattern. It started with linear designs. Then simple contour accentuating features followed. Now fully surface-conformal or hidden light guides have evolved. The future might see large surfaces, such as the bezels of headlamps, lit homogeneously using light guides.

Micro-optics

Refractive micro-optics are, according to their structural size, in the millimetre range, but they are still well above the wavelength of light. Mathematical description of such systems and their technical simulation are based on geometrical optics.

Diffractive optics are based on structures which are in the range of light wavelength or below. With these sizes the share of the diffractive phenomena outweighs the effect of refraction. This is why here, the geometrical optics no longer provides an adequate mathematical description. In this case we must fall back on the wave theory of light.

3.2.4 Styling freedom

Exterior lights give a vehicle its unmistakable appearance. They emphasise the shape of the car body by underlining the form or by consciously interrupting it. Thanks to new technologies such as pattern-free cover lenses or free-form reflectors and new illuminants such as light guides or light emitting diodes, the designer now has a wide variety of design possibilities. Many customers of new vehicles attach great importance to a daylight or night-time appearance which is typical of the brand, or even of the particular vehicle. Thus the individual styling of signal lights on vehicles offers special possibilities of increasing the recognition factor in the long-term, leading to a large variety of possibilities. Not every signal lamp can be clearly classified as belonging to one of the categories of style listed below - they often fulfil the criteria of several classifications at the same time.

Conventional

The term conventional lamp design summarises those devices that have optical structures on the patterned lens so there is no free view of the lamp from the outside. These lamps typically have filament bulbs as their light source in the optical system.

Jewel-look

The use of high-gloss mirroring reflectors with optical elements and a lens to match makes a lamp appear jewel-like. The jewel-look is produced by reflexes on:

- mirror reflectors with or without surface structure. The light distribution required is achieved solely by the reflector. The pattern-free cover lens allows an unrestricted view of the mirror reflector.
- transparent panes with structures which intensify reflection such as prisms, small radii etc. The jewel-like appearance is here not only achieved by the reflector but also by scatter lenses distinct from conventional patterned lenses.

Essentially, the design software allows not only divisions with horizontal or vertical segments, but also circular sectors and even free-form reflectors.

Line design

The narrow, long image of the lamp function is typical of line design (Wördenweber and Reinbach 1997). It can either be a line-shaped combination of light points or the flat illumination of the signal field concerned (Fig. 3.74).

Contour

The illumination of contours can be understood to be the consistent putting into practice of light guide technology for rear signal lamps. Extending line design allows the reproduction of bent or curved contours for a more exclusive styling.

In a number of styling studies for the rear end, light samples for the additional stop light spanning the whole of the rear end, as well as a complete tail lamp could already be seen. But also on the front of vehicles the position light in the headlamp shows light guide technology now in production for headlamps.

Fig. 3.74 Example of a line-design tail lamp (source: Visteon)

Fig. 3.75 Example of a position lamp with light guide (source: Hella)

So-called "edge-lighting" presents a symbiosis between contour and flat illumination. Here it is a matter of the visual emphasis placed on the contours of signal fields when the light is switched on. This can be achieved by using different luminances for signal field and edge. Light guide technology in particular, is in a position to emphasise the contour. Indirect illumination concepts for the illumination of car body parts or vehicle silhouettes also belong to contour design in the widest sense. One example of this is the so-called "under-floor illumination" of vehicles as allowed in some federal states of the US. This function produces a diffuse "light carpet" under the moving vehicle, thus making the carriageway and the contour of the vehicle visible.

Colour variations

Vehicle signal lamps must emit light in a particular colour. The colour of the emitted light is often produced by combining the light source with patterned lenses of the required colour which act as a colour filter. Patterned lenses of such lamps also show the colour of their signal functions when they are switched off. The function of colour filters, e.g. amber for indicator lights, can be made redundant by using light bulbs painted in or interference-coated with the required colour. In the case of PY21W, for example, a simple amber coat of paint serves as an absorption filter. The interference principle is based upon a dichroic filter, where the colour location is determined by the number and thickness of interference layers. In both cases, the light is of the colour defined for turn indicator lamps when it leaves the bulb. This allows the option to use clear cover lenses, for example. The same applies to LEDs or neon light sources which require no separate colour filter because the light source itself emits the required colour.

Fig. 3.76 Colour variants (source: Visteon)

Lamination techniques allow filament bulb systems to produce an even wider range of colour effects. The amount of colours of unlit lamps for example, can be reduced from three colours (red, amber and white) to two or even just one single colour (unicolour).

In order to construct a complete unicolour tail lamp, both colouring and mask techniques are combined. Masks are used mainly when the prescribed coloured location, for example on the reversing light, cannot be realised by multiplicative colour mixing with the colour of the outer lens, or when the absorption losses in the filter and patterned lens are too high. A grey unicolour tail light owes its even appearance to a tinted patterned lens with a transmission ratio of 50%.

Fig. 3.77 Tail lamp in unicolour red (source: Visteon)

Note that transparent dyes other than red and grey can be used, for example blue, green, amber or orange. The appearance of the lamp when switched off can in this way be made to match the colour of the car.

Fig. 3.78 Daytime versus nighttime appearance (source: Audi)

Future styling concepts

The design of tail lamps is becoming more and more dominated by styling aspects. Tail lamps, just like headlamps, are becoming an important element of vehicle styling, which shapes the character of a vehicle. There is now growing interest from car manufacturers to differentiate vehicles also with regard to night-time appearance.

Spotlight

Ultra-thin LED lamps offering new design freedom

On the rear and the side of the car a number of signal lamps show the other traffic participants what your car is doing, or what you are about to do. The tail light, brake light, turn indicator and reversing lamp are usually combined into a cluster referred to as the rear combination lamps. Other lamps such as the high mount stop lamp or the side turning indicator are typically single function lamps. For each lamp a large variety of different styles and designs exists. In this spotlight we will look at ultra-thin lamps with a mounting depth which is measured in millimetres.

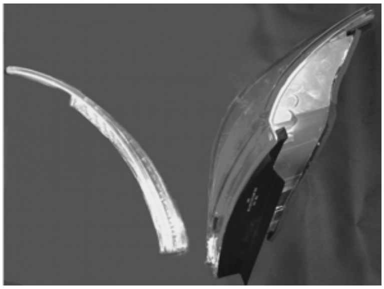


Fig. 3.79 Comparison of the mounting depth of an ultra-thin (sample) and conventional (BMW series 7) signal lamp with LED. The curvature of the outer lens is identical (source: Hella)

The light sources for ultra-thin lamps are Light Emitting Diodes (LED). Their advantages in comparison to a bulb, like quick response time (some microseconds vs. 150 milliseconds) and long lifetime (>10,000 h vs. 300 h – 1,000 h) also apply here.

Besides these general advantages an ultra-thin signal lamp offers the car manufacturer special features. A strongly reduced mounting depth of the lamp allows:

- a higher usable volume inside the boot of the car (see Fig. 3.79),
- weight reduction (less material is required for the lamp),
- a higher stability of the car body (no need to cut out holes for the lamp),
- a cost reduction in manufacturing of the car body (it is easier and cheaper just to deep-draw the sheet metal instead of cutting a hole in the

body, then rebuilding and connecting a deeper lying metal sheet surface onto the outer body afterwards).

History

Just at the beginning of this century (!) the automotive manufacturers realised that the above described advantages can save manufacturing costs. Therefore the demand for ultra-thin signal lamps gave the initial impulse for the development.

The design for ultra-thin signal lamps is strongly coupled with the rapid improvement of LED light sources. Today we have several solutions that fit many different kinds of signal lamps. The pre-development has now to be transferred to serial applications. During the next few years we expect some of the applications will be seen on the road.

Light sources for an ultra-thin signal lamp

When analysing light sources for automotive applications for the special application of an ultra-thin signal lamp, it is easily shown that only LEDs are well suited for attaining a low mounting depth of the lamp.

The mounting depth is mainly depending on the size of the light source in combination with the necessary optical system.

Bulbs with power consumption between 16 W and 21 W are the "work horses" for automotive lamp applications. Their bulb diameters are between 16.4 mm and 26.5 mm, the all over size is between 30 mm and 52 mm. Therefore the light source alone seems too big for our application. Furthermore, light bulbs are very good heat radiators emitting only a small proportion of light.

Due to the thermal emission process used in bulbs, most of the radiation is in the infrared range and only a small percentage is emitted in the visible region of the electromagnetic spectrum. The emitted heat influences all parts surrounding the bulb, such as reflectors and lenses. These parts are made out of plastics, so they need to be kept at a safe distance from the emitter to avoid negative thermal influences. If you do not want to melt your signal lamp, the distances required are so large that it is obviously impossible to design an ultra-thin lamp with incandescent bulbs as light sources.

The light emitting process used in LEDs is totally different to that of thermal emission. This semiconductor process produces heat too. However, this heat remains in the material and does not affect the surrounding optics as strongly as emitted infrared radiation does. The power consumption of LEDs in automotive applications varies between 100 mW and 1 W. This amount of heat has to be drawn off by thermal conduction.

A good thermal conductivity keeps the emitter cool. As a result the surrounding plastic materials are safe and can be arranged in the immediate vicinity of the LED chip.

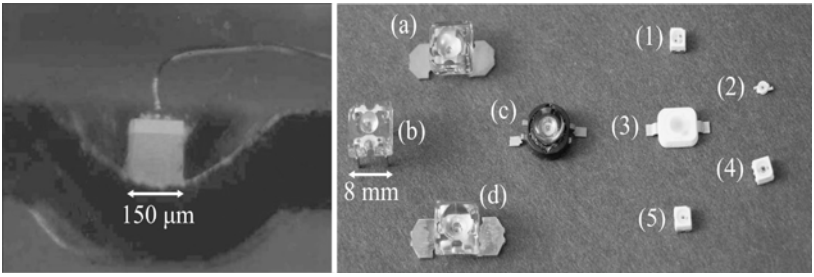


Fig. 3.80 Standard LED chip (left side) and standard LED for automotive application (right side).
(a) Snap 70, (b) Piranha, (c) Luxeon and (d) Snap 150 by LumiLeds
(1) Multi LED, (2) Point LED, (3) Dragon, (4) Advanced Power Top LED, (5) Top LED by Osram (source: Hella)

The LED dies usually have side lengths between 0.1 mm and 1mm (Fig. 3.80). Therefore the package of the LED is the main influence on the size of the LED light source. Some packages of different LED types are shown in Fig. 3.80. The package has to be designed for proper heat conductivity depending on the power consumption e.g. 50 mW for the Point LED (1 lm-2 lm) or 1 W for the Luxeon LED (20 lm-50 lm)

To design an ultra-thin lamp, the smallest possible LED package valid for your application should be used. Moreover, flat optical systems around the LED have to be designed cleverly.

For some applications it may even be an advantage to use only the LED chip and directly surround the die with special optics. In this case the die is bonded on a PC board (Chip on Board: COB) or on a metal frame (Chip on Frame: COF).

Now the right light source has been found i.e. LED or LED chips, it is time to think about the optical system for the lamp.

Design Guidelines for the Optical System

The legal requirements for the European (ECE) and US (SAE) markets define special light distributions for each signal function. These distributions do not correspond to the original light distributions of the LED light sources – an LED without further optics or just the single LED chip emits in an angular distribution that is very similar to a Lambertian radiator. A Lambertian radiator is defined as a surface that is equally bright from any viewing position in a half sphere. Therefore you need optics to collect the emitted flux and to distribute it into the right directions in space. This is usually done via reflection, refraction or total internal reflection / light guide optics (see Fig. 3.81).

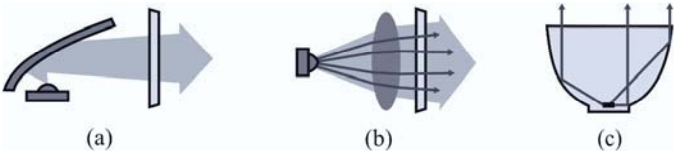


Fig. 3.81 Examples for (a) reflection, (b) refraction, (c) total internal reflection

Reflection is managed by mirror coated surfaces, while refraction is used in lenses. When total internal reflection occurs, light is reflected at the inner surface of a transparent material. The light that is coupled into a transparent body can be guided through this (possibly curved) body via multiple reflections, to special out-coupling surfaces. There the incident angle of the light rays is changed to enable the light to leave the light guide.

Independent of the kind of optics used, it is necessary first to collect a high volume of light flux and guide it into the right direction. The emitted light is collected most effectively if the optical system surrounds the light source in a wide ranging space angle. Therefore a large amount of light can be caught by the reflecting or refracting surfaces of the optics. The LED is surrounded with reflecting optics while lenses collect the light “in the front” (Fig. 3.81).

It would be optimal to surround the light source in the full half sphere. This will be considered later.

Various methods can be used for the second step, the distribution of light. Pillow optics can be used on a lens surface or on the reflector. It is possible even to work with free form reflectors or lenses to attain the necessary light distribution.

Furthermore, light guides offer a variety of options to design the right light distribution quite different to the methods described above.

If the optical system has to be flat, you have to use optics with small focal lengths (f for lenses, p/2 for parabolic shaped reflectors). In this case the size of the light source (0.1 mm to 1 mm) cannot be neglected in comparison to the focal length of the system. It is necessary to take defocusing effects into account. Sometimes this defocusing is enough to get a proper light distribution.

The recipe for ultra-thin lamps now seems clear: just take a strong LED or Chip, use a small focal length optic of the right depth and bake it into plastic. But it is not that easy. A signal function has to have a minimum area to be recognised as a signal function and not just a bright spot. The SAE regulations demand, for example, a minimum area of roughly 50 cm^2 for the tail-, stop- or indicator lamp.

This requirement leads to two different options:

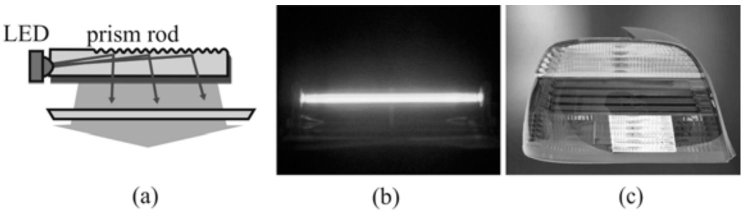
- Use a number of smaller optical systems and light sources and combine them to a matrix shaped signal function or
- Take just one LED and ensure that your new optical system is flat and wide enough to fulfil both requirements (small depth and large area).

There is more designing to be done after the optical design is finished. The housing and mounting of a lamp need careful design as well. Unfortunately their design solutions are so specific for each costumer and application, that the description would exceed this spotlight. So instead some examples of ultra-thin LED rear lamps with different technologies are shown.

Light guide prism rods

A good example for a first ultra-thin signal function and even for the first application of the light guide technique in tail lamps (BMW 5 E39) is a so called prism rod (Fig. 3.82).

The LED is positioned at the side surface of a rod shaped light guide. The emitted light passes this in-coupling surface and is guided along the inner surfaces of the light guide via multiple total internal reflections. Eventually the light is reflected onto prisms situated at the back of the rod. The surface of the prisms reflects the light in a direction such that the light can pass the front surface of the light guide. The mounting depth of the optical system is mainly dependent on the size of the mounted LED board positioned at the side of the prism rod. The mounting depth of the optical system in the application shown is less than 15mm. The whole signal lamp however, is much deeper because the other signal functions are equipped with incandescent bulbs.



(a) (b) (c)

Fig. 3.82 Prism rod light guide optics. (a) physical principle, (b) illuminated single rod, (c) application in the BMW E 39 tail lamp (based on source: Hella)

Light guide reflectors

It is possible to manufacture the LED package itself as an optical system for an ultra-thin signal lamp instead of using a secondary optical system.

In this case the LED body surrounds the chip as a total internal reflecting system (Fig. 3.81c). If several LED bodies are combined to a solid matrix (Fig. 3.83a) a signal lamp without any further optical system is designed. The electrical connections of the dies are done in COB or COF technique (Fig. 3.83b). The advantage of such an ultra-thin lamp is the combination of light sources, optics and electrical/thermal connections in one single body.

This can be done most effectively by combining optics and COF in one (injection) moulding process.

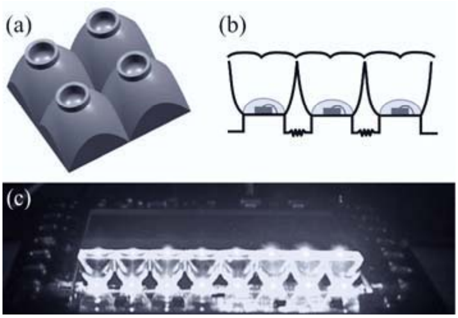


Fig. 3.83 (a) Matrix of total internal reflectors, (b) connection of the Chips via COF (sketch), (c) row of a multiple emitter body in COF (based on source: Hella)

A sample of such a COF tail-/stop-/indicator lamp fulfilling all legal SAE requirements showed a depth below 9 mm (see Fig. 3.84).

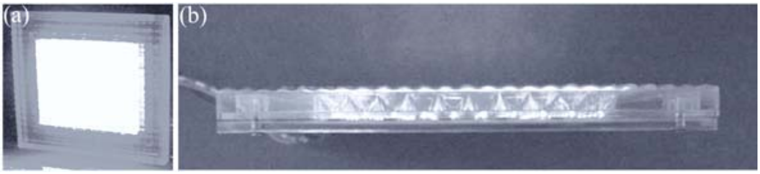


Fig. 3.84 Sample of an SAE tail-/stop-/indicator lamp of 8.8mm depth in COF technology; (a) front view, (b) side view (source: Hella)

Light curtain

A light curtain perfectly suits applications that demand a lower intensity such as ambient illumination, tail lamps or side markers. The LEDs are positioned at the side of a plastic sheet used as a light guide element. The emitted light is coupled into the sheet and leaves the whole sheet via multiple total internal reflections. On the back side you can find out-coupling elements. These elements scatter the reflected light in the direction of the front surface where it leaves the light guide (Fig. 3.85a).

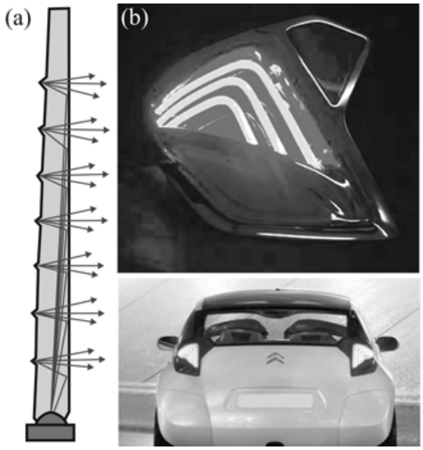


Fig. 3.85 Light curtain: (a) physical principle, (b) application as a tail light (homogeneous surface) in combination with prism rods (bright lines) in the Citroen show car Air Play (source: Bologna Motor Show 2005)

The depth of the optical system is mainly defined by the LED board (~10mm); the light curtain itself can be much thinner.

The light curtain offers a high degree of freedom in styling such as shaped 3-dimensional contours and an exceptional homogeneous appearance. This is shown in the tail lamp of the Citroen C Air Play show car (Fig. 3.85b), first presented at the Bologna Motor Show in 2005. In this lamp a light curtain for the tail light is combined with prism rods (brake function) positioned in front of the curtain.

Lens optics

For our application a special group of lenses, the so called Fresnel lenses, are a good choice. Similar to light guides, these lenses can take advantage of refraction and total internal reflection. What is the difference between a normal and a Fresnel lens?

For a flat optical system a small focal length is required. A lens in this case would usually be strongly convex and therefore very thick. A Fresnel lens is in principle just a reduced “skeleton” of a normal lens: only the refracting surfaces (divided into rotational symmetric zones) are left, while the rest of the lens bulk is reduced to a flat piece of equal thickness (Fig. 3.86). A Fresnel lens is therefore much thinner than a normal lens.

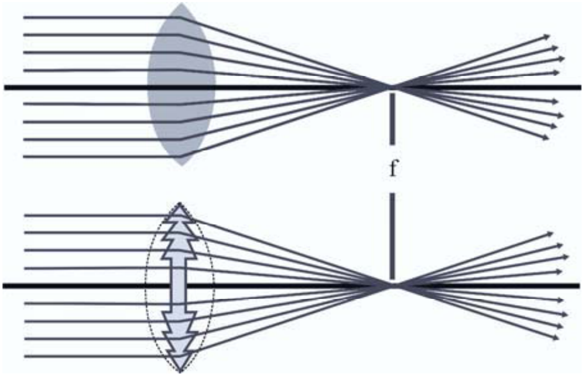


Fig. 3.86 Comparison of (a) normal and (b) Fresnel lens

There is another advantage of Fresnel lenses in comparison to normal lenses. In the outer lens region the prisms can be used as reflecting “teeth”.

The light is then reflected at the outer surface via total internal reflection. A Fresnel lens therefore, can combine both refraction and reflection.

The special lens design for an ultra-thin lamp usually has an additionally curved shape to surround the light source in a largest possible space angle. Fig. 3.87 shows two examples. The first has a row of low power LEDs, the second has one high power LED. The high mounted stop lamp samples (Fig. 3.87a) are designed with 30 Point LEDs. The function fulfils the legal requirements without much effort and the mounting depth of the optical system is below 5mm.

The second optics (Fig. 3.87b) is done with one Luxeon LED. It fulfils the legal requirements for any signal function. The area of the lens exceeds 50 cm^2, although the mounting depth of the optical system is below 18 mm. While the first example needs no additional distributing optics, the second is equipped with pillow optics on the outer surface.

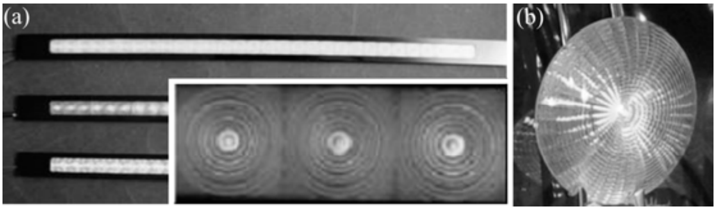


Fig. 3.87 Ultra-thin lens systems: (a) samples of thin line high mounted stop lamp optics with 30 LEDs (mounting depth <5 mm), (b) lens with one high power LED for all major signal functions (mounting depth <18 mm) (based on source: Hella)

Outlook

The examples described show a high variety of different ultra-thin optics design valid for signal lamps. The development is still proceeding. New light sources such as organic LEDs (OLEDs) will give new impulses for future developments in the years to come.

The demand for styling will be to design ultra-thin lamps that give the image of depth in the optical system. This is to preserve the “third dimension” of the signal lamp styling instead of just tailoring flat “two dimensional” graphics.

3.2.5 Adaptive signal lights

The basic concept of rear signal lighting is about 50 years old. Modifications have only arisen in terms of the increase in the level of luminous intensity and the integration of additional functions, such as rear fog lamp and third stop light. There is plenty of discussion about the rear fog lamp, which is often switched on at the wrong time, which illustrates the fundamental problem of a signal lighting in general. The intention had been to make the vehicle visible even in thick fog. Therefore a very bright signal was chosen with a luminous intensity 50 times greater than that of the tail light. There is plenty of room for improvement if we consider that the following traffic is dazzled if the lamp is switched on by mistake, or that the rear fog light has a higher central luminous intensity than the stop light.

With sensors and adaptive control the system can be improved greatly. It can be adapted to match the lighting conditions for day, night and twilight. It can be adjusted to suit the prevailing weather conditions, such as rain, snow or fog. And it could provide more refined information for different driving situations such as changing direction, stopping or warning. The adaptive signal can be generated using the following principles:

- Variation of the signal surface
  If the surface of a signal is constructed using several light sources (typically light emitting diodes), there is the additional possibility of passing on qualitative information to following traffic by means of signal fields of different sizes. The more light segments are illuminated, the stronger the total luminous intensity.
- Regulation of the luminous intensity and luminance
  If the surface area of the signal lamp is kept constant, the luminous intensity of the lamp can be controlled by surrounding factors. Thus, for example, a stop light in a dark night should be illuminated with a

lower luminous intensity level, whereas in bright sunshine a multiple luminance is needed in order to recognise the signal safely. The intermediate stages are regulated accordingly.

The electronics of today's modern vehicles already provide part of the information which is necessary for an adaptive signal lamp system. Apart from recording movement status, some vehicles sense surrounding illuminance for the control of the headlamp light and interior lighting. Depending on the choice of the concept and the functions regulated, further parameters may need to be incorporated.

3.3 Interior lighting

In the recent past, the technology of vehicle lighting has gone through a phase of great change. Front lighting possibilities were greatly extended by the gas discharge lamp. Rear signal lighting was revolutionised by the LED. Interior lighting is currently experiencing a similar trend towards new light sources and designs.

3.3.1 Installation and function

Most vehicles today still give the impression that interior lighting remains restricted to a single light aperture. One reason for this is that until a few years ago, interior lighting was actually provided by a central main lamp in the roof lining. Functionality was primary: the illumination of the passenger compartment was purely designed to facilitate orientation in the vehicle. Technical and design requirements on the lamp were relatively independent of the vehicle class. This is still true for the majority of vehicles belonging to the lower vehicle categories.

The technical complexity of interior lighting systems is also frequently underrated, since the integrated electronics are not externally apparent. However, due to ever-increasing advances in technical possibilities, once simple lighting systems have evolved into highly intelligent interior lighting systems. Design and technical requirements have also greatly increased. Modern interior lamps also offer functions such as ambient permanent illumination and non-glare workplace lighting.

In cars today there is space for more than just one interior light. Lighting functions such as permanent ambient lighting or glare-free workspace illumination are becoming more and more common.

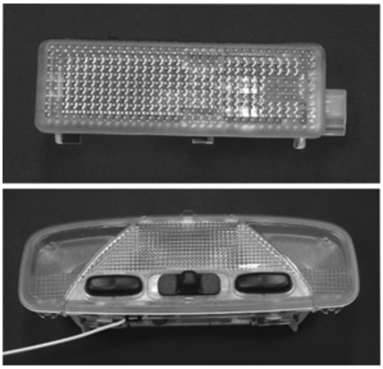


Fig. 3.88 Dome lights for typical low end vehicles

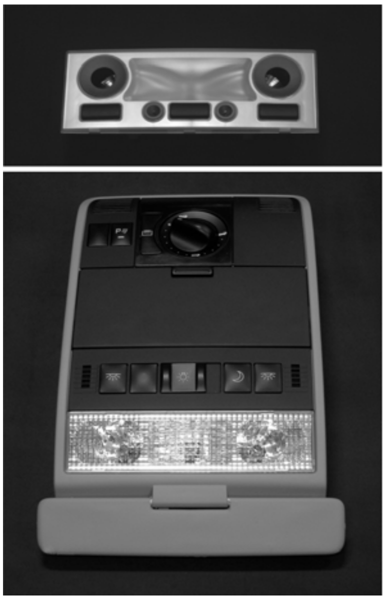


Fig. 3.89 Multifunctional interior lights for typical high end vehicles (source Hella)

Ambient lighting creates the adequate ‘working atmosphere’ for the driver if the physiological aspects are taken care of. The following figure illustrates that it can improve orientation in the vehicle.

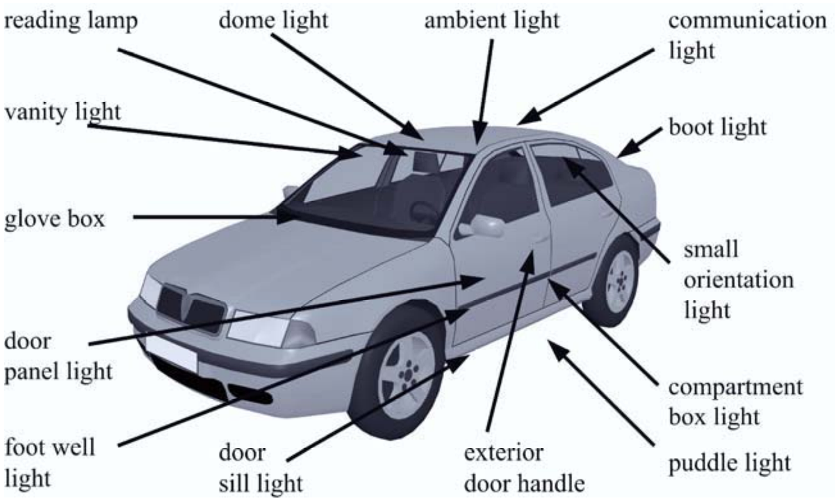


Fig. 3.90 Different interior lights in a modern vehicle

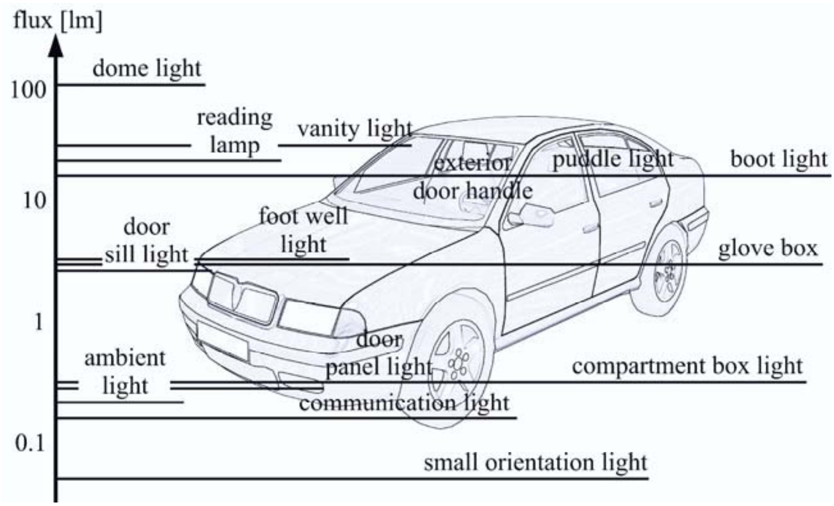


Fig. 3.91 Typical light flux requirements for different interior lights

Interior lighting can improve a feeling of safety and security. Needless to say special care has to be taken when designing interior lighting, not to draw away attention from the driver or impair his visual ability. Ambient interior lighting should not produce stray light for example, by unwanted reflection in the windscreen. Also to be avoided are light levels in the interior that will change the adaptation levels in the drivers visual field.

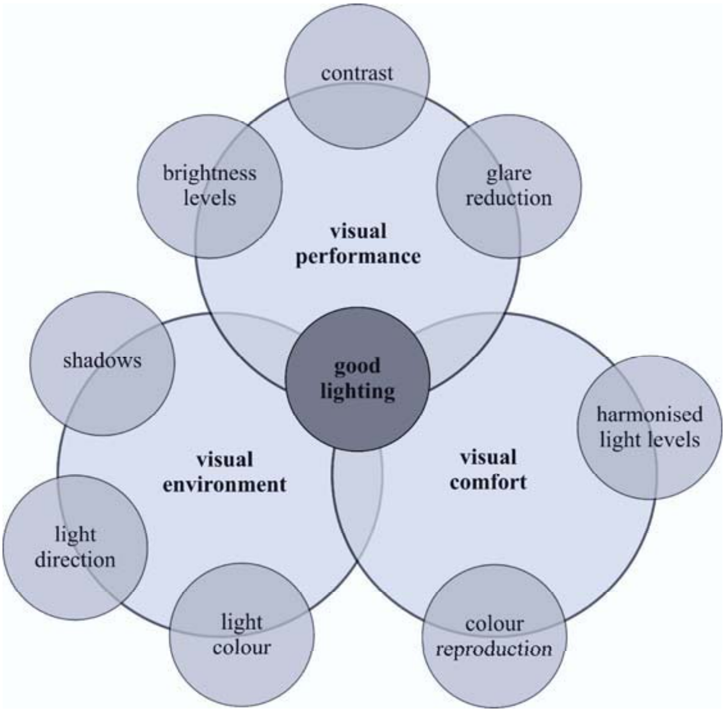


Fig. 3.92 Quality criteria for interior lighting

There are no binding legal regulations for the lighting of passenger compartments. The various interior lighting functions are tailored to the vehicle in a harmonisation process between the vehicle manufacturer and the supplier, taking into account the lighting quality criteria: the visual performance depends on the overall brightness, contrasts and low glare; visual comfort rises with good colour reproduction and harmonised lighting levels between the central and peripheral field of vision. The quality of the visual environment is created by the light colour, the lighting direction and any shadows cast.

By analysing typical vehicle situations, the following four interior light function groups can be identified. In a "logical lighting" concept, several individual functions can be logically combined in groups. For example as an entrance aid, the foot well lighting can be increased to a high setting, with the threshold lighting and the reading lamp assigned to the seat also switched on, in addition to the illumination of the zone immediately in front of the door.

entry/exit	functional lighting
typical functions: -courtesey light ('puddle lamp') -door lock -foot well -door warning **performance criteria:** -no shadow -average luminosity 1-10lx -neutral light colour -average colour rendering (CR>50) -low glare -homogeneous illumination	**typical functions:** -interior main light ('dome light') -reading light -work/playing light (rear) -make-up light -glove box -boot **performance criteria:** -no shadow -clear delineation of the illuminated area -for reading/working liminosity 50-100lx -for interior/make-up luminosity 10-20lx -neutral light colour -good colour rendering (CR>80) -no glare -homogeneous illumination
ambient lighting and orientation	**light control**
typical functions: -switches -handles -foot well -storage -down light for console -door down light **performance criteria:** -low luminous intensity for driver area 0.1 cd/m² for rear passenger area 1 cd/m² -illuminance dependent on interior colour -light colour warm white, yellow-green, or orange-red -no glare	**typical functions:** -situation dependent lighting -illumination of scenarios -reduced irritation to the eye -ensuring adaptation and accomodation for eye movements

Fig. 3.93 Interior lighting functions and their lighting requirement

Entry and exit illumination

For reasons of orientation and safety, the vehicle could be visually emphasized by means of appropriate lighting when approached in the night, with handles for doors and boot lid lighted.

“Coming home” lighting

A “guiding” pathway of light brightening the footpath to and from the vehicle would provide extra safety, especially in the dark or in an unfamiliar area. Technically, this function could be realised by a delay circuit fitted to already existing headlamps or lamps, such as the position lamp or dipped beam and reversing lamps.

Courtesy light

Illumination of the direct entry and exit area and the handle recess before the door is opened makes sense as an independent lighting function, or functionally-linked to the “going home” function. It can be activated when the vehicle is approached, after the door lock has been released by remote control. The door handle, the handle recess, or the external mirror are all possible installation sites for the lamps. In case of a rear approach, the licence plate light with raised illumination could be used in addition to a separate lamp.

Entry and exit area

When the door is open, additional illumination of the direct entry or exit area is desirable for reasons of comfort and safety, allowing possible uneven patches, puddles etc. to be recognised. These lamps can be optimally installed below the door pocket or below the door itself.

Threshold illumination

Marking of the threshold when the door is open, switched via the door contact at night, is beneficial in two ways. Firstly, a possible obstacle in the entry area is detected, meeting a safety requirement. In the case of vans, cross-country vehicles, and commercial vehicles in particular, the thresholds can be very high. Secondly, illuminated lettering or the representation of the vehicle logo can underline the worth of the vehicle and increase the customer’s brand identification. The threshold illumination can be easily realised using either electroluminescent strips or light guides.

Door warning lamp

Signalling whether doors or loading openings are not closed is highly useful to following traffic when a vehicle is at a standstill, although up to now there have been no legal regulations in force. During entry and exit, the increased width of the vehicle is indicated by a red warning light installed at the door. Due to the variable door-opening angle, the door warning lamps have to cover a very wide and rather flat illumination area of high intensity. Red LEDs with front lens optics are strong potential light sources, helped by the small installation space required. Passive signalling is also possible by the additional integration of a reflex reflector.

Functional illumination

Functional interior light applications address fundamental lighting requirements in the vehicle. At night the instrument panel illumination must allow important information to be read; the reading lamp must allow road maps to be consulted; and the loading compartment illumination must facilitate the search for the spare wheel in case of a puncture, or for pieces of stored luggage, picnic etc.!

Central interior lamp / roof node

In the past few decades, the central interior lamp, usually installed in the roof of the vehicle, was of rather minor importance with regard to lighting technology and design. However, in recent years this has started to change. As an eye-catcher for the passengers, the shape and visual appearance of the lamps can be adapted to the overall vehicle design. The desire to have "jewel look" headlamp and tail lamp design is extended to the passenger compartment. General trends towards diffuse or extensive illumination of the passenger compartment via invisible light sources are therefore adapted to this application. The large-surface illumination of the two light disks of the current luxury vehicle is a desired design feature.

The functional development of the central interior lamp began with a simple delay circuit which controlled soft on / soft off dimming of the central interior light, thus supporting the eyes in the adaptation process and allowing the driver quickly to get his or her bearings in the vehicle. Invisible from the outside, complex electronic functions have been added to the lighting function of the central interior lamp. These include climate, light, and rain sensors, passenger compartment monitoring, automatic emergency call, radio-controlled garage door opener, control of dimmable interior mirrors, and motor control for sliding and lifting roofs. Because of the connection to the vehicle's data bus and the integration of the appropriate electronics, the central lamp has already become a complex operating unit which, thanks to its "central lamp intelligence", can also control other lights.

In the future, "infotainment" components, such as hands-free talking, information displays, transmitters for wireless headphones, and connections for game consoles will be integrated in ever-more complex roof nodes. Modular construction with replaceable lighting and electronics modules on the one hand allows adaptation to different customer requirements without problems, while on the other it permits uniform styling across different model series.

Reading lamp

At the moment, the reading light in many vehicles, especially in the rear compartment, is insufficient and not ergonomically adapted to its requirements. The requirements for optimal design of reading lamps are steadily growing: the reading lamp in the rear, for example, is often used as a working light or as a light for children. Non-glare lamps with a clearly-defined and homogenous illuminated area of high intensity do not impair the driver's view through the windscreen and rear window by direct dazzling or reflection.

Cosmetic mirror illumination

Although in many vehicles today there are cosmetic mirrors for the front-seat passenger, driver, and sometimes for the rear-seat passengers as well, integrated functional illumination has not yet become the norm. A cosmetic mirror illumination must not dazzle the driver, but instead provide homogenous and non-glare illumination of the field of vision, and furthermore provide excellent colour rendition. The very good colour rendition ability of filament bulbs at the moment especially excludes the use of other, narrow-band light sources for this function.

Instrument illumination

Instrument illumination has recently become an identification feature for car manufacturers. In addition to permitting the instruments to be seen clearly at night, manufacturers are now trying to distinguish themselves from other competitors by means of coloured instrument panels, a process made possible by the various light colours of light emitting diodes that have meanwhile become available.

Convenience illumination

Glove compartment illumination is standard in most vehicles. A contact switches on the light when the glove compartment is opened. Additional recess pockets in the doors or in the rear compartment with sliding or folding mechanisms can be illuminated following the same principle to facilitate searching. Simple filament bulb lamps are usually used for this function, but white LEDs or coloured LEDs matching the colour of the interior can also be used.

Boot illumination

Boot illumination is standard equipment in many vehicles and is usually switched on by a contact when the boot lid is opened. To provide sufficient illumination when the boot is loaded, for example with pieces of luggage, several light sources have to be distributed in the boot. After several tragic accidents involving children locked up in boots, the US now requires easy access of the interior emergency opener. Delay circuits for existing boot illumination or a separate handle lamp represent technical possibilities which could permit this function to be realised.

Engine compartment illumination

A function which is not widely implemented but is entirely practical, is an engine compartment illumination that operates when the hood is open. This would allow the driver for example, to check the fuse box or to top up the oil or windscreen wiper water at night. The lamps used in this area have to be made of temperature-proof material and in capsule form to resist surrounding influences such as oil, fuel, water, and de-icing fluid.

Orientation lighting

Orientation lighting functions cannot be clearly distinguished from ambient lighting functions. The dividing line between these functions is blurred, and some functionalities address orientation and ambient light aspects simultaneously. With the rising number of controls in the passenger compartment, the danger of the driver becoming confused is also growing. Optimal illumination allows the driver to see the movement of his or her hand when searching for a control element, and thus quickly and securely to coordinate the movement. Illumination of the foot well and package trays at night can additionally address comfort aspects which, by integrating the lighting components into an interior light staging concept, can contribute to the creation of an ambient passenger compartment illumination – a feel-good atmosphere.

Controls

The switches and controls required by the driver have to be illuminated at night in such a way that the symbols on them are clearly recognisable, thus allowing them to be promptly used without a time-consuming search. Contour representation or illumination through the switches and controls, combined with a slight incident light, are ergonomically favourable solutions.

As part of both the orientation and ambient lighting, a soft incidental light, similar to a “waterfall”, can provide subdued lighting of the centre console area. The shadows cast by the switches create spatial depth, allowing structures to become discernible. This allows the distance to the controls to be estimated, visually guiding the operator’s hand and thus ensuring that illuminated symbols no longer “hover” indeterminably in space.

In terms of comfort and safety aspects, other operating elements can also offer appropriate lighting positions for the passengers, e.g. marking of the ashtray and the cup holder, the openings of various package trays, or the marking of the belt lock. As many of these functions involve the illumination of very small, defined areas and thus only require small luminous fluxes, LEDs can ideally be used. Another reason for the use of light emitting diodes is their long life which results in low service costs.

Foot well illumination

Illumination of the foot well addresses ambient aspects in addition to offering an orientation aid. On the one hand, it provides an entry aid for driver and passengers and reduces the risk of looking for objects that have been dropped into the foot well. On the other, subdued lighting contributes to the creation of a feeling of space. The lower area of the passenger compartment, which would otherwise be dark, thus becomes perceptible. Optimal design of foot well illumination must avoid steep entrance angles which might result in disturbing reflections and highlights on clothes and shoes. If illumination is appropriately flat, only the floor will be covered by a “light sheen”.

Integrated into “logical lighting”, the foot well illumination can be increased when the door is opened to provide an additional entry aid. After the door is closed, the illuminance can be dimmed to an appropriate ambient level.

Appropriate positions for installation of the foot well lamps are in the area below the instrument panel, the seats, or the area of the centre tunnel or the side thresholds. Both filament bulbs with low output and increasingly LEDs, can be used as light sources.

Ambient lighting

In contrast to the illumination of important controls, ambient lighting functions are not absolutely necessary to drive a vehicle, and there are correspondingly no regulations regarding them. Of course, the driver’s perception at night must not be reduced by distracting effects such as reflections on the windows.

An ambient interior lighting atmosphere which is physiologically and psychologically optimised should convey feelings of security, comfort, and value. Indirect illumination of the roof, illumination of the B and C columns, or a slight lighting on the side surfaces of the doors can contribute to the improved well-being of driver and passengers. The driver will tire less when driving at night due to the reduction of contrast achieved between the vehicle interior and the outside.

When certain areas are illuminated the passenger compartment becomes more detailed, appears larger and more structured. The objective is to make the passenger compartment perceivable as a whole during the ride, and for the vehicle’s occupants to feel good in it even during long drives.

3.3.2 Filling space with light and colour

Non-glare features and an attractive design have for a long time been the quality criteria when it comes to the lighting of buildings. However, directly transferring all this experience to the interior lighting of a vehicle is difficult, because the level of illuminance in any vehicle is significantly different.

Light colour

In addition to the luminance level, the light colour plays an important part. The colour of the interior lighting can have an influence on the subjective assessment and the actual perception of the passengers. Interior lighting in architecture takes account of the fact that colours create characteristic thought associations and have clear psychological effects on human subjects (Keller 1999). These associations with cold and warm colours are of importance in the vehicle.

Fig. 3.94 Ambient interior created by a cold light colour (source: Visteon)

Illumination with a high colour temperature e.g. light produced by white light emitting diodes, electro-luminescence foils, or fluorescent lamps, creates an austere technological ambience; whereas illumination with a low colour temperature e.g. by means of a dimmed filament bulb, contrastingly creates a cosy, homely feeling.

Several factors influence how we perceive colours. These are in particular luminous intensity, size and type of lit surface and the colour spectrum of the light source.

Colour rendition

The choice of light source also has a great influence on the perceptibility and the appearance of objects. Coloured objects appear different if illuminated by different light sources. When it comes to interior lighting this is especially important to the passengers and the functioning of the passenger compartment, and should therefore not be underrated.

If the colours are rendered identically in accordance with a reference light source, we talk of the colour rendition value 1, or the colour rendition index Ra = 100. Light sources with different spectral distributions, the light of which makes coloured objects appear differently, have a colour rendition value of less than 1 i.e. Ra <100.

To enable the various materials used in the passenger compartment (such as wooden patterns, fabrics, carbon or brushed metal surfaces) to be accurately identifiable as such at night, light sources with a good colour rendition must be used. In contrast, light sources with a narrow-band spectrum have only limited colour rendition abilities.

3.3.3 Special light sources

Regarding the technical implementation of interior light concepts with new lighting functions, new requirements for the light sources and optics to be used arise. For example, smallest possible packaging, and high intensity and homogenous illumination are requested. Thermal loads, installation space requirements, and design requirements require innovative lamp concepts.

- Filament bulbs
  are still the light source primarily used for functional lighting applications, such as the interior light and reading lamp. The advantages include the broad-band spectrum, ambient light colour, high luminous flux available, and low cost. On the other hand, the short service life and reduced efficiency, the large installation space needed, and the high temperatures generated, are amongst the disadvantages of filament bulbs.

- Light emitting diodes (LEDs)
  are especially suitable for small orientation light functions because of their minimal size, long service life, low power consumption, minimal heat generation, and quick response. The light colours available today already cover a large share of the functions. With white LEDs and a growing range of luminous flux there is technically no barrier for LEDs to be used for all interior lighting functions.
- Organic LEDs (OLEDs)
  use organic materials to generate light in contrast to the inorganic light emitting diodes described above. Because these structures are polymeric and not crystalline, they open up completely new possibilities for design. Furthermore, organic LEDs are characterised by a long service life and low energy consumption. They are especially well suited for background illumination and luminous displays. At the moment, it is too expensive to apply this technology extensively. Another disadvantage is that the light output declines with service life. However, further development will possibly allow the realisation of extensive lighting solutions with OLEDs in the passenger compartment in the long or medium term.
- Electroluminescence foils (EL)
  are characterised by minimal installation depth, low energy consumption, homogenous luminance, and the large number of colours that can be produced. Due to their poor light output and relatively unsatisfactory colour rendition of white light, coupled with temperamental critical temperature and humidity behaviour (i.e. they tend to short-circuit if moisture penetrates), they are not suitable for functional lighting applications. However, EL foils can be used for extensive ambient and diverse orientation light functions. In contrast to OLEDs, EL foils are typically supplied with a voltage of 115 V at a frequency of 400 Hz. To guarantee electromagnetic compatibility in the on-board power supply network, precisely dimensioned ballast is required.
- Fluorescent Lamps
  (here: Cold Cathode Fluorescent Lamp – CCFL)
  are characterised by high light output with relatively low power consumption. A large number of coloured and white variants are available, using various fluorescent substances in the inner wall of the tube. Figure 5.14 shows the drawn-out shape which make CCFLs appropriate for the representation of contours as well as general lighting purposes. The electronic ballast (inverter) in the vehicle required to operate the CCFL must be precisely dimensioned to rule out EMC

problems. However, there is only a limited possibility of dimming CCFLs, while operation at low temperatures is unreliable, so that separate pre-heating of the tube is required to start the lamp. The mercury contained in the lamp necessary for operation is also problematic, but the light output of the mercury-free lamps that have been developed remains about 50 % less than that of conventional CCFLs.

3.3.4 Control systems

With the continued development of automotive engineering on the one hand and of information technology on the other, the amount of visual information offered to the driver is constantly increasing. Radios with traffic updates, gauges indicating speed, revs, temperature, and fuel reserve are today supplemented by car telephones, mobile radios, display areas for navigation aids, air-conditioning equipment, and an on-board computer. In the luxury vehicle category, more controls are used in the rear compartment, further increasing the number of light sources there as well.

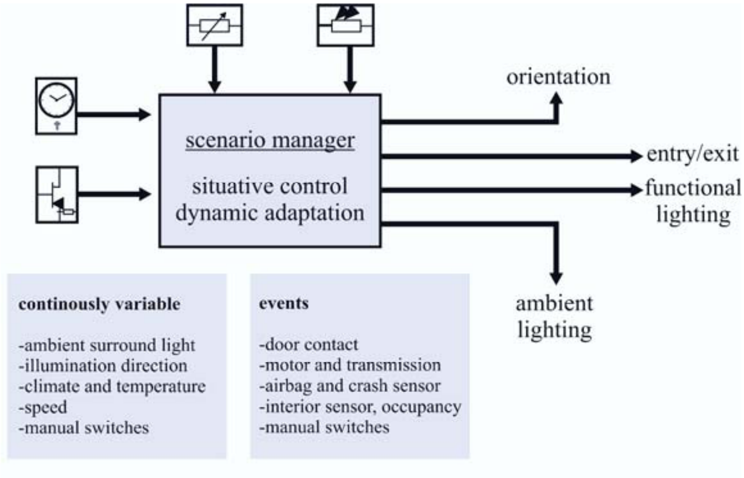


Fig. 3.95 Model of an interior lighting control

Dynamics and automation are consequently fundamental elements in future passenger compartment lighting concepts. Since manual control of the various interior lights would prove impractical as well as uncomfortable for the driver, it is absolutely necessary to minimise the number of manual interventions required. An example of a solution is the control system shown in Fig. 3.95, which switches or dims the individual or groups of light sources automatically in certain situations.

Because the human eye needs a certain time to adapt after a sudden change of the light situation, this control system should delay the switching processes and create “soft” transitions taking into account the adaptation process of the human eye. This on the one hand avoids bothering the driver by the large number of lit light sources and, on the other hand leaves a discernible visual contrast between the illuminated objects and the exterior in the dark.

By integrating various sensors and actuators, important direct and indirect influences and variables acting on driver and passengers alike, such as weather conditions, speed, number of occupants, driving condition, or personal preferences, can be taken into account in a passenger compartment light control system. For a variety of reasons therefore, dynamic changing of the interior lighting in the motor vehicle is a desirable feature. As development cycles become ever shorter, it becomes necessary to assess new lighting concepts using either mock-ups or virtual reality before they are implemented. A control model is a good basis for this.

An intelligent control system can additionally suppress superfluous signals. For example, the controls for the parking light or parking brake should only be illuminated when the vehicle is at a standstill. Dynamic adaptation of the intensity of the ambient passenger compartment lighting in relation to the ambient brightness is another comfort and safety feature.

In addition to the input and output variables and the control functions, the planned hardware concept should already be taken into account during the design of the system to make efficient use of the resources. This especially applies here because interior light components are distributed all over the vehicle. In the following, a possible hardware concept for passenger compartment light control is explained in more detail.

The functions of the passenger compartment light control are distributed between several electronic control units (ECU), located at different positions in the vehicle. These receive and process the data of the surrounding sensors and control the actuators near the respective control unit. The power of the signals for the actuators is adapted in the respective control units. For more efficient use of resources, the control units can contain the functions of several different control systems in parallel. Communication between the control units and the simulation system is made via the vehicle’s data bus, typically a controller area network (CAN) or a local interconnect network (LIN). One of the control units assumes the master function for the passenger compartment light control and contains the central sequence control system. The inputs and outputs of the various control unit slaves are almost identical (digital and analogue inputs, PWM outputs) and functions (Abel et al 2000)

Interior lighting is facing a highly dynamic development in that attitudes are beginning to change, thus leading to a greater interest in that product area. Another factor is the vast potential raised by the increasing amount of information available inside the vehicle. Lighting will therefore become an even more important issue when it comes to the planning of interior vehicle designs and may even turn into one of its integral aspects.

3.4 Ever-changing technologies for luminaires

Changes in technology enabled many of the changes in lighting. It was and still is the development of the light sources that drives change today. In addition electronics and mechatronics are giving us the means to change lighting and slowly turn it into something that is safer and more ergonomic than it used to be.

3.4.1 Man made light sources

Today there are optimised light sources for a vast range of different purposes, although the principle of light production remains the same. Energy in the form of electromagnetic radiation is released if charged particles (in the following text electrons are presumed) move from a state of higher energy to a state of lower energy. Before this, the electrons must have reached this higher energy level by receiving an influx of energy. In the following examples, different types of light sources and the method of the corresponding influx of energy will be described in more detail.

Thermal emitters

Most of the light sources we are familiar with are thermal emitters, whether they are candles which transfer chemical energy into heat, or electric filament bulbs, which simply use an electric current to heat the filament. What then, is the principle behind these thermal emitters?

Every solid body emits permanent radiation whose continual spectral composition depends mainly on its temperature. At a temperature of 25°C (corresponds to 298 K) practically all the radiation emitted lies in the invisible far infra-red range. The higher a body's temperature, the larger the portion in the shorter wavelength range and thus in the visible spectral range. In addition, the total light output increases with temperature. The exact physical correlations are described by Planck's radiation formula, developed by Max Planck in 1900.

At a temperature of 1000 K just a small part of the emitted radiation is in the visible wavelength range of 380 nm to 780 nm; a noticeably higher share is only achieved at multiples of 1000 K. The relative distribution in over the visible range determines the colour impression. At a temperature of 1000 K the light given off appears red, resembling glowing charcoal or a hot brake disc. At 3000 K, a temperature at which most metals have already melted, the glow appears white, although this is still a long way from the colour impression of sunlight (about 6000 K).

Since electric filament bulbs are thermal emitters, their efficiency increases with the temperature of the filament. The melting points of relevant materials set natural limits: the melting point of tungsten for example, is 3650 K. At this temperature, a thermal emitter emits just about 24 % of its total radiation emission as light. This is a theoretical maximum value that is never reached in practice. Without taking the necessary precautions, a filament bulb operated at such a high temperature will only have a short service life. Under these conditions a considerable amount of the material from the filament is volatilised during use and leads to a clearly recognisable blacking of the glass bulb. There has to be a compromise found between service life and light output. The filament temperature and thus the light output can be increased by using filling gases such as xenon.

The major problem with thermal emitters is the low working efficiency of less than 10% and consequently a low luminous efficiency of typically less than 30 lm/W. The incandescent bulb is a thermal light source with a tungsten filament that glows when electrical energy flows through it. The luminous flux of a standard bulb is low and the service life limited by vaporised tungsten particles from the filament, which deposit on the inner surface of the bulb. Incandescent bulbs such as the P21W with a luminous flux of 450 lm are used for signal lamps.

Spotlight

Entropy strikes

Lights have a finite life

It is a sad fact that light sources do not last forever. The result is that it is not uncommon to come across vehicles with an incomplete set of lights. Such vehicles pose a hazard. The nature of the hazard depends on which lights have failed. Some examples are

The one-eyed monster

A vehicle with only one headlight is a hazard for three reasons. For the driver of the vehicle, the amount of light put on the road will be reduced and the distribution of that light changed. The consequence is that the visibility ahead will be reduced, particularly in the areas primarily lit by the failed headlamp. For a driver approaching, it will be difficult to determine the distance and movement of the vehicle, the ability to make such judgements accurately being less when there is only one point of reference than when there are two or more. The driver approaching will also experience some uncertainty about what sort of vehicle is approaching and consequently what is to be expected. Is the single headlight that of a motorcycle or is it a car with a broken headlamp?

Brake or turn

A vehicle with a failed brake light is a hazard, particularly if the failed light is the central high mounted brake light. The onset of a brake light requires a rapid response from a following vehicle, so anything that increases the reaction time to the onset of the brake light is detrimental. In general, the closer the brake light is to the following driver's line of sight, the faster the onset will be detected. The central, high-mounted brake light will often be the brake light closest to the following driver's line of sight.

The above is true for all countries, but where brake lights and turn signals are the same colour, a failed brake light poses an additional hazard. Specifically, the onset of a single brake light may be confused with the onset of a turn signal. Such confusion will delay the necessary response.

The unexpected change in position

A vehicle with a failed turn signal is also a hazard. Such a vehicle may fail to give sufficient warning to a vehicle behind that it is about to change position. A failure to indicate a change in direction or lane can mislead the following or adjacent driver about intentions, who may in consequence, attempt an inappropriate manoeuvre e.g. overtaking.

Halogen bulbs

By adding small quantities of halogen atoms (e.g. iodine), the blackening of the glass bulb by tungsten vapour can be further reduced. Here a characteristic chemical property of the tungsten halides is used for this purpose. Tungsten iodide (WJ_2) is gaseous at temperatures above 250°C and decomposes into tungsten and molecular iodine at high temperatures. The volatilised tungsten from the filament is thus present as gaseous tungsten iodide in the region of the glass bulb and cannot precipitate. If these molecules reach the area around the hot filament, the WJ_2 decomposes and the atomic tungsten precipitates on the cooler places of the bulb. With the same service life, halogen bulbs can be used at higher temperatures and thus have a correspondingly high efficiency level. Since the halogen cyclic process only works at a glass bulb temperature of more than 250°C, halogen bulbs have a relatively small glass bulb.

Fig. 3.96 Incandescent bulb P21W and halogen bulb H21W (right)

The luminous flux radiated by a filament bulb can only be controlled to a certain extent by the supply current. If the supply current is reduced, the temperature of the filament also falls and with it the luminous flux. In addition, the efficiency of the lamp is reduced and the colour location of the light moves toward red. If the supply current is increased, the luminous flux and the efficiency are increased, but the service life is drastically reduced. The service life or the failure quota of a bulb is very important.

The service life and the light output strongly depend, amongst other things, on the current through the filament. As a rule of thumb: if the current through the filament is increased by 5 % the luminous flux is increased by 20 %, the power consumption increases by 8 % but, at the same time the service life is dramatically halved.

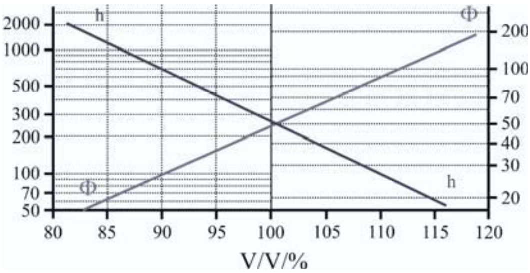


Fig. 3.97 Service life and luminous flux as a function of voltage

The nominal filament bulb voltage itself determines both service life and efficiency. If a filament bulb is designed for an operating voltage of 42 V instead of the usual 12 V, this affects the geometry of the filament. If the original power consumption is to be maintained, the length of the heating wire must be greatly enlarged or the diameter significantly reduced. Both modifications reduce the service life. The demands made on the mechanical characteristics for use in driving cannot be fulfilled or only with very great difficulty. In addition, the characteristics for an optical system like a car headlamp are worse for a longer filament than for a short one.

Many halogen bulbs such as the H1 or H7, have only a single filament. These are used in dipped beam headlamps or fog lamps. Dual filament bulbs such as the H4, are capable of alternating between low and main beam. A cap covers that portion of the dipped beam with the highest glare potential. Halogen bulbs have to be handled with care as some of them contain gases under pressure. Also, any traces of oil or grease on the glass surface can damage the glass during the high temperature operation.

Spotlight

The bulb can make a difference

"The headlight of a car is only as good as the light source in it" – this is common sense among developers of car lighting equipment. While the great majority of automobile manufacturers support this statement, many consumers underestimate the role of the light source for automotive lighting. Unfortunately, even within service personnel there is sometimes a tendency to say: a bulb is a bulb. As a result, many headlights degrade after some years of service, as replaced bulbs do not comply with the standards set by car manufactures and set makers. Furthermore, bad quality bulbs are present in the aftermarket. While promising features like “Xenon-Light” or “Laser-Light” they do sometimes not even reach the minimum requirements of the ECE or SAE regulations. Moreover, many of these inadequate bulbs cause glare for the oncoming traffic. As a result, safety and comfort are major subjects affected by automotive replacement bulbs.

This spotlight is about incandescent bulbs for automotive application and takes a specific look at halogen bulbs for headlamps. They are the most common light source for front lighting in cars and probably will be for many years to come.

History

Electric automotive lighting has its roots in the early 20th century. The first effective bulbs with double filaments for high and dipped beam were developed in the early 1920s. The next milestone was passed in 1936 when Sealed Beam headlights were introduced in the US. The first halogen bulbs found their way into cars after Philips started the production of the H1 bulb in 1960. H2 and H3 followed. Osram was first with a two-filament-bulb in halogen technology. It was named H4 and had its market introduction in 1970. In Europe over the next 20 years no major developments took place. Finally in 1993 the H7 was presented. The technology of this bulb was the base for many new bulbs and improvements of the older types H1 to H4.

In the US, halogen bulbs were first introduced in the early 1980s when the DOT allowed other headlamps systems than Sealed Beam (Bauer 2003).

Problems in application

Good automotive bulbs, especially halogen bulbs for headlights, are manufactured with low tolerances and high accuracy. The products of the big manufacturers General Electric, Osram and Philips (just to name the three most important) are found in almost all new cars. The shelves of supermarkets, car accessory-shops and service stations are however, filled with various bulbs from many almost unknown companies.

In collaboration with a leading set maker for headlamps, the author of this spotlight conducted extensive tests of car bulbs. Special attention was paid to those from sources other than the big three manufacturers (Lorek 1999). Many of the aftermarket bulbs showed severe defects in performance, tolerances and protection from glare. Some types promising bluish light produced a range of different colours instead, mainly violet. The usable light for the headlamp was comparably low, in some cases even below the minimal requirements of the ECE regulation. Glare was at the same time twice as high as produced by good bulbs. It was obvious that the light distribution of those bulbs did not follow the regulation of ECE, although being labelled with the required E-sign! The E-sign declares the conformity with the regulations of the Economic Commission for Europe (ECE), an organisation of the United Nations. A figure behind the letter E indicates the country of certification. Examples are 1 for Germany, 2 for France, 11 for Great Britain, 43 for Japan and 48 for New Zealand. This shows that the ECE regulations also apply in several countries outside Europe.

Fig. 3.98 E-sign in its conventional form (left) and as allowed if the space is limited (right, from a bulb together with the certification number)

The problem of those inferior bulbs seems to be the Conformance of Production (COP) that a manufacturer has to guarantee. While it is quite easy for the authorities to control the COP at plants in their own country, this is almost impossible when production is abroad. Even aftermarket-bulbs carrying E-signs from European countries are often produced in Far Eastern countries.

One of the few ways to go for a good quality automotive bulb is to buy parts only from well-known companies with a good reputation. Car manufacturers are urged to point out more clearly that consumers and service personnel should use bulbs from the same source as the manufacturer does. There could be a recommendation in the driver’s manuals or markings on the cases of headlamps. Locks and lids on the sets could carry a decal or other mark saying “Use only bulbs made by GE, Osram, Philips”, or whatever brand the car manufacturer trusts. Many car companies already give recommendations for a special brand of motor oil, spark plugs, batteries or tyres. Not one of them would allow dubious brake pads or steering components. Why should it not be possible to take just as much care about incandescent lights as well?

Strangely enough, some countries are not rating bulbs as safety components. It should be a common goal for industry and traffic-safety organisations to change this.

Another commitment to the safety function of automotive bulbs could be to put a set of spares for the most important bulbs in every new car. This would follow the same guidelines that apply to warning triangles and First-Aid-Kits. Some countries are already demanding spare bulbs and car drivers would appreciate a nice integrated storage place for them. Spare bulbs supplied by the car manufacturer are a good guideline for which type and brand to use or buy as a replacement.

A new amendment to the ECE-regulations is urging car manufacturers to ensure the easy replacement of bulbs (ECE 2003). An onboard spare makes a change even easier.

Another threat endangering safety is the premature burnout of bulbs. This is not only a problem of inferior bulbs from dubious manufacturers. High-performance-bulbs, sometimes called ‘upgrades’, pay the price for more and better light in the form of a shorter lifetime. To achieve an acceptable balance between both is a challenge for the industry. However, high-performance bulbs are a way of compensating for the creeping loss of performance of headlights due to ageing. This is usually the result of corrosion on the reflector, which leaves a slight ‘haze’ on the otherwise shiny surface. Scratches on the lens are another common reason for this deterioration in performance. In other words: a (legal) high-performance bulb can keep the headlight of an older car close to the effectiveness it had when new. Note, however, it does not prevent excessive glare due to ageing.

While some of the new bulbs have some technical advantages, the greater variety in itself is causing problems in the aftermarket and repair shops, as well as to service personnel and car owners. Some rarely used types like HB4 (in Europe) or HB2 (in North America) may not be in stock or even unknown to a dealer. Sometimes it is even possible to force the wrong type of bulb into the socket, although the construction of the bulb and the headlamp should prevent this. This could severely affect the performance of the light and is very likely to cause glare.

Table 3.4 (Dis-)Advantages and typical applications of several bulbs

	advantages	**disadvantages**	**typical applications**
Standard bulb	All-rounder in automobile headlighting. Low costs and reliable function. Long lifecycle.	Lighting on the road is somewhat lower than state-of-the-art would allow	Original equipment, general replacement. Standard bulbs are sufficient for projection systems. No advantage by using other bulbs.
Upgrade bulbs as Premium or SilverVison by Philips or Osram Silverstar	Up to 50% more lux, depending on the type of bulb and the construction of the headlamp.	Shorter lifecycle. High price. No relevant improvement in ellipsoid (projection) systems	Compensation for the loss of performance of slightly degraded headlamps

	advantages	**disadvantages**	**typical applications**
Bluish bulbs (Osram Cool blue; Philips BlueVision)	Up to 400 °K higher colour temperature. Therefore whiter than standard. Partly comfortable for elderly car drivers	Nothing like as good as the often-promised light of xenon -bulbs.	Design-orientated applications.
Yellowish bulbs (“Allweather”)	Comfortable to some car drivers	About 5% lower performance. Tendency to unwanted colour-effects.	Very rarely found today
Long life bulbs	Longer lifecycle in cars with high operation voltage	About 10 to 20% lower performance, compared with standard.	Cars with day-time running light (DRL)

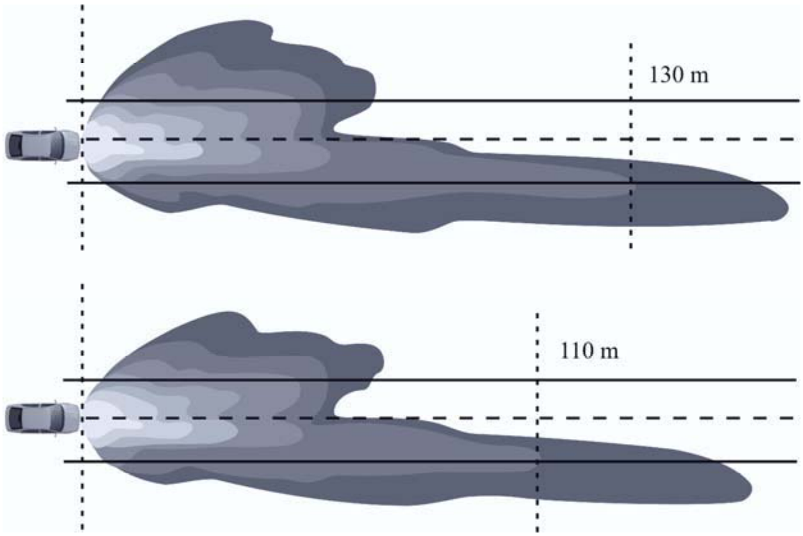


Fig. 3.99 Difference in range between H4 standard bulb and upgrade (Philips Premium, top) in a new headlight (Lorek 2004)

Outlook

LEDs have replaced tungsten lights in many automotive applications during the last few years. Therefore, the question arises: what prospects do the traditional light sources have in the future?

In the interior, the LED has already gained superiority in recently developed cars. Here today only very few bulbs are still equipped with a tungsten filament. Some higher intensity reading lamps or instrument clusters may use them. Many others, especially all indication or warning lights have already been replaced by LEDs or will be within a short time.

Exterior signal lighting is following the same trend, but not as fast. Tungsten filament bulbs are still the most common light source for direction indicators, stop lights and reversing lights. Position and rear lamps are however, more often realised using LEDs. The reason is quite simple: today, it is still expensive to replace e.g. a 21 W bulb with a solid-state source. Rear lamps can be nevertheless realised with LEDs at prices comparable to those of conventional 5 W bulbs. This situation will change within the near future as prices for high-intensity LEDs drop. Incandescent bulbs will lose their dominant role within signal lighting, but not for sometime yet in head lighting.

The bulb industry is still investing resources in developing new halogen bulbs for automotive applications. After the physical limits for light output have already been approached, the research is focused on easier handling, fewer requirements for space and longer duty-cycles. A good example for recently developed bulbs for head lighting is the series H8B to H11B. While offering the same high level of light output these new bulbs, produced first by Osram and Philips, are no longer connected by plugs, sockets and loose cables, but by an easy-to-use snap-in arrangement. H8, H9 and H11 are becoming important in newer headlamps. They are specially designed to provide specific types of light. The 35 W H8 is intended for fog lamps, while the H9 (65 W) offers 2100 lm and is therefore the strongest halogen bulb for automotive applications. It is a good choice for the main beam. Dipped beams can be powered by a H11, which emits 1350 lm (H7: 1500 lm).

The most common application for conventional halogen bulbs are the headlamps. Especially modern types of halogen bulbs like H8, H9 and H11 offer good opportunities for a state-of-the-art headlight. Of course, high intensity discharge light sources (xenon) offer superior performance, but the higher costs will limit their usage to cars from the upper compact class upwards. As a result, the tungsten filament bulb will have a future. Halogen bulbs will remain the dominant light source in head lighting. The great majority of cars will use them for many years ahead.

Fig. 3.100 H9B bulb with Snap-in technology. The lack of a cap on the top of this up-to-date-bulb indicates that it is a specialist for main beam usage

Up to the early 1990s, halogen bulbs (or even their predecessor in non-halogen technology) were the only source for automotive lighting. Therefore, aftermarket needs for those bulbs will continue for a long time. Today, even bulbs for 6 V are still available – over 35 years after the last cars with a 6 V power supply had been manufactured. In addition, the old R2 non-halogen double filament bulb for head lighting is still manufactured. This type of bulb is in such a high demand, that the industry developed a replacement version with halogen burner (Philips Visio, Osram Halostar). Today's automotive bulbs will follow the same development, as the demand for replacements will be even higher than in the past. Day-time running lights will be mandatory in more countries and it will be realised in most ways using a dipped beam.

Gas discharge light sources

Typical light sources in this category are fluorescent bulbs and high intensity discharge light sources, also referred to as xenon light sources, which are being used increasingly for car headlamps. The principle of light production is the same in both types of bulbs.

In gas discharge lamps gaseous atoms are excited by electrical discharge. When the atom (or ion) returns to its basic state it emits energy in the form of light. This is generally a line spectrum, since atoms only have a limited excited state. In the simplified Bohr atomic model, electrons can only move on certain limited orbits with a corresponding energy level, around the nucleus of an atom. A change between these two states is only possible through absorption or emission of exactly this difference in energy.

Typically a gas discharge light source consists of a glass tube with electrodes at both ends. The tube is filled with rarefied gas which can be offset with Hg or sodium vapour. In contrast to filament bulbs, gas discharge lamps have special ignition devices which produce the free electrons necessary for the current flow. When switched on, a voltage is placed on the electrodes, triggering an ignition spark. The free electrons produced by this are accelerated through the electric field between the electrodes and collide with the gaseous atoms in the tube. Depending on the energy, these atoms are either left in an excited state or ionised. This latter process causes more free electrons to be produced which are in their turn accelerated, and so on. This leads to a cumulative ionisation of the gas which leads to an ever-increasing current through the lamp. To avoid destruction of the lamp should the current increase uncontrollably, electronic devices with a current-limiting function are used. After the ignition process there is a constant current through the tube due to the current limitation. This means that a certain fraction of the gas atoms is always in an excited or ionised state. Some of these atoms return spontaneously to their basic state or recombine with free electrons. Both processes release energy in the form of radiation which can lie in the ultra-violet or in the visible spectral range, depending on the type of gas used and the gas pressure.

The gas discharge lamps used in xenon headlamps are based on high-pressure gas discharge. The distance between the two electrodes is comparable in size to the filament of an H7 bulb i.e. the dimensions of the luminous volume are very small and very high luminance can be achieved. This is particularly advantageous for use in headlamp systems which depend on precise image relationships.

Fig. 3.101 Xenon gas discharge light source D1S and halogen bulb H7 (right)

Gas discharge lamps are very efficient compared with thermal emitters and luminous efficiencies of 90 lm/W are typical. They also offer a certain amount of freedom for the colour composition of the radiated light. By adding suitable materials the appearance and the contribution of different spectral lines can be controlled. For automotive use a colour temperature of approximately 4100 °K, similar to daylight is used; they only appear bluish in comparison in the dark because the widespread halogen headlamp systems have a yellowish colour tone.

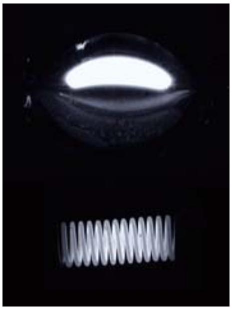


Fig. 3.102 comparison of arc of a gas discharge light source (above) with the filament of a halogen bulb (below)

The spectrum of gas discharge lamps in xenon headlamps also contains ultra-violet radiation which can, for example, be aggressive towards plastic headlamp covers. For this reason the glass bulb of modern xenon lamps is doped with appropriate dyes which filter the unwanted UV share of the outgoing light.

Light emitting diodes

Electrical energy is directly used with semiconductor light diodes to excite electrons, which will then revert to their basic state, emitting light at the same time. A light diode is a classical electrical diode which is operated in the pass direction. In the area of the boundary layer, high-energy electrons can recombine and emit light.

LEDs are very small and are operated using low voltages. In the radiated spectrum only light of one wavelength appears, which for simple LEDs is characteristic of the semiconductor used. Due to the close interaction between the semiconductor atoms, the wavelength of the radiated light is nowhere near as sharp as with gas discharge lamps. The light output depends to a large extent on the operating temperature (the lower the better) and the quality of the semiconductor crystal.

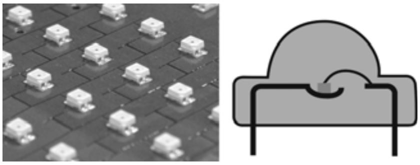


Fig. 3.103 Light emitting diode as surface mount device (left) (source: Osram) and principle design of an LED

Light diodes are highly effective as red signal lamps since they radiate the prescribed colour directly. Conventional filament bulbs need a red colour filter which absorbs about 75% of the incident luminous flux. Characteristic values, such as service life, of typical light sources in car illumination are compared below.

Table 3.5 Typical properties of different automotive light sources

	luminous efficiency (lm/W)	**average service life (h)**	**rise time n/ms**	**supply voltage (V)**
incandescent bulb for turn signal (P21W)	18	400 (T_C)	200	13,5
halogen bulb for turn signal (H21W)	25	440 (T_C)	200	13,5
halogen bulb for dipped beam (H7)	25	550 (T_C)	200	13,5
xenon, high intensity discharge (D2S)	90	2000 (B_{50})	0,2	85 (ignition 23 KV)
LED	20	10000 (B_{50})	2	2

A great advantage of the usual LED for car signal illumination is that it delivers the required red or amber signal colour immediately. If however, blue or white light is required, the situation is different. In 1990 there were practically no efficient semiconductor materials available which were able to emit light in the blue spectral range. The light of the popular red LEDs cannot however, be converted into blue light, since blue light has a higher energy level than red light.

With the advent of blue and ultra-violet LEDs this situation has changed. Here phosphor materials capable of absorbing part of the blue light and radiating green, yellow or red light instead can be incorporated into the transparent LED cap. For example, the mixture of green, red and the rest of the original blue light is made into a white colour impression by additive colour mixing.

An impressive race has begun for high performance white LEDs. It is now possible to create headlamps with relatively few LEDs. Current technical and commercial drawbacks are being removed.

3.4.2 Electronics for lighting

For a long time lighting was mainly a product composed of metal and plastic, bent into place, filled with optical surfaces and topped with decoration. Since the early 90s however, lighting requires more and more electronics in order to:

- drive new light sources (power electronics) such as light emitting diodes (LED) or discharge sources (xenon / xenon)
- shape the light dynamically for adaptive front lighting systems (AFS) or more intuitive signal lights (e.g. brake-force display)
- create a 3-dimensional luminous source consisting of individual light sources or luminescent foils
- integration and use of sensors and actuators like levelling sensors, temperature sensors, stepper and dc motors and moving coils
- Interconnection of the lamps to a network that allows control and diagnostics

This section outlines the role of electronics within lighting.

Electronic drivers for light sources

For the electronic engineer the light source is just an actor. Headlamps and tail lamps are just one of many components of the electrical installation. Up till the end of the 90s, electric lamp switching has been mainly via the contacts of light switches or relays. In extreme cases this means that for every light function there must be at least one cable leading to the switch in the passenger compartment, through which often all the required current flows. These days, light switching increasingly takes place electronically, using transistors (typically MOS-FET) or so-called high-side switches, which apart from switching quietly and without wear and tear, also make the dimming and diagnostics of the lamps possible. These functions are usually achieved by switching filament lamps on and off quickly, a method known as pulse-width modulation (PWM). By changing the pulse-width repetition rate (the time between switching on and off), the effective voltage on the filament bulbs can be varied.

Gas discharge lamps need more costly boosters for the voltage supply, known as the ballast. The ballast starts the lamp with an ignition impulse of up to 23 KV and then drops to an operating voltage of about 80 V (400Hz) in normal use. Electronic regulation makes sure the electrical power consumed by the lamp is kept stable.

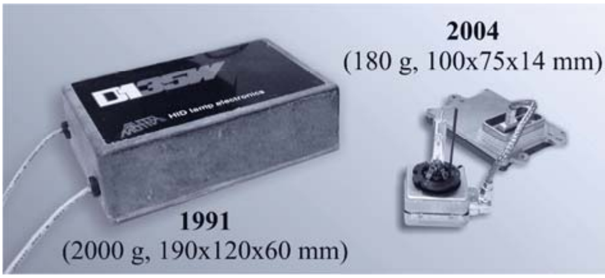


Fig. 3.104 Ballast for gas discharge light source

Light emitting diodes do not enjoy the 12 V typical for incandescent lamps in the car. Signal lights and headlamps with LED also require dedicated driver electronics.

Spotlight

LED control

Introduction

Automotive lighting in North America has experienced tremendous changes in the last couple of decades. For a good half a century automotive lighting consisted of a traditional filament bulb. This was usually part of the round or rectangular standardised sealed beam commonly found. In the late 70s the sealed beam turned form incandescent to halogen. In the 80s lamps were allowed to follow the aerodynamic design of the vehicle. However it wasn't until the 90s that alternative light sources came into use for automotives, starting with High Intensity Gas Discharge (xenon) lights for front lighting or the neon fluorescent lamps for signal lighting.

Now advances in high power LEDs have led to the use of LEDs not only for simple functions inside the vehicle, such as switch illumination and warning indicators on the dash panel, but also in exterior lighting starting with Centre High Mount Stop Lamps (CHMSL) and then signal lamps. With the advent of new light sources, the simple 12 V DC from a vehicle battery can no longer directly power these new sources such as xenon, Neon and LED. This spotlight looks at the types of LED control that are being used for LED exterior lighting.

History

Electronically seen, a bulb is simply a resistor. Automotive bulbs have been optimised for the operating voltage of the vehicle of 12 V. Below 12 V, the bulb consumes less power, hence produces less light. At voltages higher then 12 V, the bulb consumes more power, hence produces more light. However the life time degrades significantly. The chart below shows how a bulb operates in an automotive electrical environment.

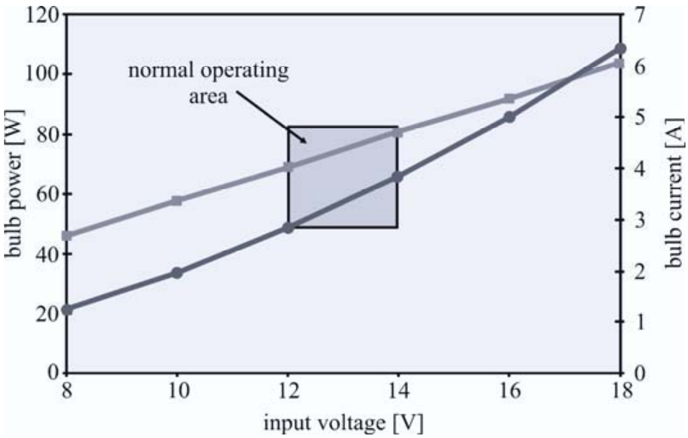


Fig. 3.105 Automotive dipped beam bulb (55 W) operating parameters

The typical operating area of the bulb is between 12 V to 14 V. With this type of a load, the bulbs are traditionally powered directly from the vehicle battery. Vehicle voltage above 14 V commonly occurs as the battery ages or when the alternator or other charging system is defect. Luckily, the bulb is easily replaced.

General rules of LED application

The LED principally is a DC controlled device, similar to a bulb. Alternating current (AC) voltages are not applied to LEDs. But the LED behaves quite differently. Unlike an incandescent bulb, an LED is a non-linear electronic device. The current in the LED is proportional to the luminous flux. The LED Voltage-Current (V-I) transfer function is shown in Fig. 3.106.

The safe operating area of the LED is shown in the Figure above. LEDs run in the safe operating area, produce predictable light output and the junction temperature remains below the design operating temperature.

Note in Fig. 3.106, the V-I curve has a very steep slope. That is, a small increase in voltage changes the LED current significantly. The voltage and the current increase together, hence more light is emitted from the LED. This holds true up to a certain point. Once the maximum LED junction temperature is exceeded, the LED will malfunction and incur irreversible damage. Thus it is crucial to ensure that LEDs are controlled in the area defined above.

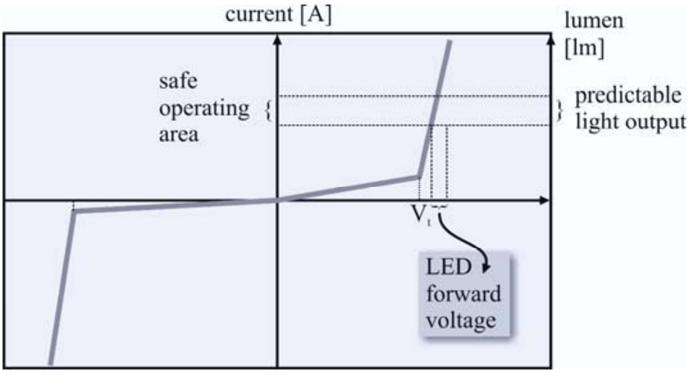


Fig. 3.106 Generic LED Voltage vs. Current (V-I) curve

The power of the LED is calculated as follows:

P_{LED} = Current in LED · Voltage across LED

Application of LEDs in Automotives

As shown in Fig. 3.106, between zero volts and the voltage threshold V_t, the LED light output is unpredictable and typically not rated by the LED supplier. The normal operating area above the V_t threshold is where the LED produces light. So how can we control the LED in such a narrow operating range? The vehicle battery voltage may range beyond 14 V or reach

19 V for failed alternator and go to 26 V during a double battery jump start!

In simple applications, the LED is controlled by a simple resistor placed in series with the LED. The value of the resistor is chosen such that the LED current produces enough light for the function of say, a high mount stop, stop or tail function. Electrically this is shown in the figure below.

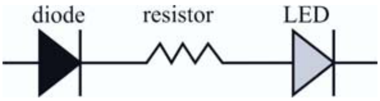


Fig. 3.107 Resistor-Diode representation of LED control

In Fig. 3.107 only a single LED is shown. More than one LED is typically connected in series or as an array. The number of LEDs is determined by the style, the function and the type of application, and of course by the type of LED, which can vary greatly in light output.

The diode shown in Fig. 3.107 prevents the LED from reverse voltages that occur in vehicles. This occurs, for example, when a vehicle battery is jump started, and the jumper terminals are accidentally reversed. A bulb does not need this protection since it is a simple resistor. A LED, however, would be permanently damaged under reverse voltages.

This simple form of control works very well for signal functions. These are low power applications, typically under 6 W of overall power. Depending on the type of LED, the Resistor-Diode control scheme is not very efficient from a power dissipation standpoint. Under normal operating voltages, about 30-40% of the power is being dissipated in the resistor, the rest in the LED.

A different scheme has to be used with high power exterior functions with LEDs such as fog, day-time running lamps, dipped beam or main beam. These use between 10 W and 60 W of power.

There is a choice of other forms of current control for LED’s such as Resistor-Diodes with Pulse Width Modulation (PWM), linear regulators, linear regulators with PWM and finally switching regulators. Within switching regulators there are even further different forms of topology, such as the Buck converter where output voltage is less then input voltage; Boost converter where output voltage is greater than input voltage; or Buck/Boost where the output voltage could both be lower or higher than the input voltage.

For high power LED controls, a switching regulator is the most efficient form of LED current control, as an efficiency of greater than 75% can be obtained from them. The type of switching regulator used depends on the type of LED and the number of LEDs used for the function.

In the switching regulator the vehicle input voltage is converted to AC and then back to DC. This requires a complex integrated circuit that performs this function with some external electrical components such as inductors, resistors and capacitors. High Power switching regulators use commonly available IC's in the electronics industry suitable for the automotive environment.

Outlook

LEDs for automotive applications are rapidly becoming more efficient and better performing, thus reducing the number required for lighting functions. This helps to make the function using LEDs more cost effective. With the LED the control is also evolving. As LED applications proliferate into automotive exterior lighting, very specific ICs will be designed to control the LED current very accurately. This will help to make electronics smaller and more cost effective, helping the overall application of LEDs

Lighting bus

The concept of "decentralised light switching" is based on the linking of headlamps and light control modules by means of the CAN-bus (Controller Area Network) or LIN (Local Interface Network). The switch signals are produced in a conventional way by a light switch and translated locally into a bus-signal. All the lights can now be controlled locally using only 'power', 'ground' and the bus-signal. This attempted solution to switch the consuming source locally offers a whole range of advantages: lower logistic and service expenditure throughout the vehicle, due to reduction of the variety of wiring harnesses and directed diagnosis capacity; notable simplification of the individualisation of the vehicle with regard to the scope of the technical lighting functions (software and hardware-implemented); reduction of the wiring harness expenditure, since only two supply cables and two cables for the CAN-bus signal are required per headlamp; and short connection routes which are immune to interference between the consumers and their drives, and between sensors and their evaluation points.

First and foremost this development means the separation of energy and information flow. Whereas up to now the information needed to switch on a consumer was guided through one cable, which also delivered the necessary energy for operation, there are now cables available which permanently guarantee the energy supply, while other cables are exclusively used for information transfer. These are mainly the bus-leads such as the CAN-bus or LIN. The information range is thus no longer limited by the number of cables available. In addition to an immense increase in the information transfer capacity, a bi-directional data exchange (control information to the consumer, status information from the consumer) has become possible.

42 V

The ongoing discussion on the potential introduction of a vehicle electrical system with a voltage of 42 V is taking place because future high-load consuming sources, such as electric valve drive and electric brakes (brake by wire), will overtax an on-board mains with only 12 V nominal voltage, due to the high currents they require. This leads to the question of how the light sources in the vehicle are to be supplied. While at first a dual voltage electrical system with its own 12 V-circuit arm has been planned, there is no telling what improvements long-term development may bring. The following options are available should the light sources have to be supplied from a pure 42 V network:

Since today's xenon lamps already require a booster, this only needs to be made in a different size.

LEDs in most lights are supplied with preceding resistors. With resistors of the appropriate size, larger power losses result. In contrast, if the supply is by means of electronic components, it will be sufficient to change the size of the resistors.

The greatest problem is filament bulbs. Filaments designed for an operating voltage of 42 V are so long that they cannot be used for vehicle illumination, due to their mechanical characteristics. The optical image of a larger filament is significantly worse. Consequently a suitable voltage supply must be produced locally, possibly by dc-dc transformers producing 12 V direct voltage. The above-mentioned PWM operation is still under discussion for this particular function. There are, however, many questions regarding the behaviour of filament bulbs under these particular conditions which are yet to be satisfactorily answered. The fact that most light sources in vehicles will need their own electronic booster in the future, further increases the importance of decentralised light switching. This would allow the production of a suitable supply voltage and the drive of the light source could be combined in one control unit.

3.4.3 Materials for lighting

Coach lights were made from metals such as brass. Today a lamp is predominantly made of plastic material. Even the glass for lenses is now changing over to polycarbonate. Here are a number of examples for the current choice of materials.

Spotlight

Exterior lighting – Lenses and reflectors history

This spotlight provides a short overview of the historical development of materials and processes for the main optical elements for exterior lighting (headlamps and tail lamps) and possible changes in the near future.

History

The industrial production of lamps for vehicles started in the second half of the 19th century. The light source was a kerosene flame and the illumination of the road was pretty limited. These lamps already had the main components we find in headlamps today: light source, reflecting mirror and cover lens. The first cars with petrol engines used the same headlamps as horse drawn coaches. The speed of cars increased quickly and better road illumination became more and more important. The light sources changed from kerosene to acetylene and finally to electrical bulbs. Headlamps with bulbs were standard in the 1920s.

The lenses and reflectors also changed, but the development was less dramatic. Glass as material for lenses was almost exclusively used until the end of the 20th century. The glass lens was the main optical element for automotive headlamps, because reflecting mirrors had only simple circular parabolic shapes. This limitation was caused by the forming process of reflectors. The first industrial method was the spinning of brass sheet. The rough surface of brass reflectors had to be ground and polished.

Fig. 3.108 Headlamp glass/metal (1960’s)

The reflecting layer was prepared by electroplating in very dangerous cyanide baths. In the 1940s a new process for headlamp reflectors was developed: the brass sheets were replaced by steel sheets and an electroplated silver layer was replaced by varnish coating and vacuum deposition of evaporated aluminium.

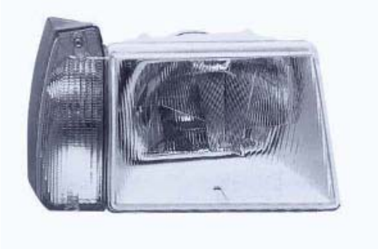


Fig. 3.109 Headlamp glass lens, metal reflector, plastic housing and front indicator 1970’s

The second half of the 20th century may very well be called the “age of plastics”. The tail lamps usually used similar processes and materials. The housing of tail lamps was produced from zinc plated sheet metal. Later the housings were made from die cast electroplated zinc alloy. The lenses were made from coloured glass. Plastic materials began their successful adoption by automotive lighting in tail lamps. The polymethacrylate and polycarbonate material for lenses offer good optical properties and good stability. The advantages were so huge that transparent plastics very quickly replaced coloured glass. When looking at the housing/body with reflectors, the situation is different. The glass lenses are purchased parts from specialist suppliers, but the bodies for tail lamps are produced in house at the set maker. This could be one reason why this replacement process took longer than expected.

Fig. 3.110 Tail lamp plastic lens and metal reflector and housing 1960’s

Fig. 3.111 All plastic tail lamp 1970’s

Table 3.6 Reflectors for headlamps

reflectors for headlamps				
period	**base material**	**coating to smooth surface**	**reflective coating**	**protective coating**
1900 - 1950	brass	copper (electroplated)	silver (electroplated)	none
1950 - 1983	steel sheet	baking varnish (dipping, spraying)	aluminium (vacuum deposition)	vacuum deposition (SiO, HMDS) or varnish
1983 - now	bulk moulding compound (thermoset)	UV cure varnish (flow coating, spraying)	aluminium (vacuum deposition)	vacuum deposition HMDS
1990 - now	PEI, PES (thermoplastic)	none	aluminium (vacuum deposition)	vacuum deposition HMDS
remarks:				
SiO - protective layer prepared by reactive evaporation of silicon monoxide in vacuum				
HMDS - protective layer prepared by plasma enhanced polymerisation from vapour of hexamethyldisiloxane (HMDS)				

Reflectors

For more then 30 years the steel sheet was the main material for headlamp reflectors. In 1972 the patent for bulk moulding compound (BMC) material was announced by the British company Lucas. This BMC material with a high content of fillers, predominantly glass fibre and chalk, is based on polyester resin. This thermoset material is hardened in a mould.

The BMC material features excellent properties:

- shrinkage after moulding is almost zero
- thermal expansion coefficient is low
- temperature resistance is about 200ºC without any melting
- injection moulding is a very similar to the process for thermoplastic

However, the surface quality of BMC moulding was not good enough for direct metallisation and therefore painting was necessary. The coating process for BMC reflectors is simpler than for metal reflectors (Xu et. al. 2001). By 1989 this production process of BMC reflectors was considered the industrial standard. The BMC material allowed the creation of all optical functions for low and main beam and the removal of all optics from the lenses. Currently thermoplastic materials try to replace BMC, but with low success because the prices of thermoplastic are too high.

The full potential of BMC is still not utilised (Mapleston 2001). In the future further improvements of the surface quality are expected by using new plasma enhanced vacuum deposition processes.

Fig. 3.112 BMC reflector

Lenses

For more than 100 years headlamp lenses were made from soda-lime glass. Glass has been used for lenses since the Middle Ages and it offers very good long-term stability, but it is brittle and the production process is not simple. Finally today, we have the production of glass lenses developed to high productivity full automated production, from raw material through liquid glass and finally glass press.

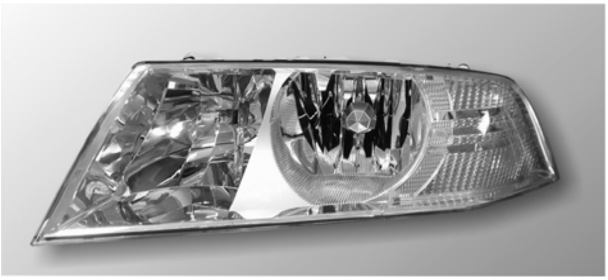


Fig. 3.113 Headlamp with polycarbonate plastic lens and BMC reflectors (source: Visteon)

Table 3.7 Lenses for Headlamps - Europe

lenses for headlamps – Europe		
period	**base material**	**protective coating**
1900 - 1994	soda - lime compound glass	none
1994 - now	polycarbonate	thermo - or UV- hardened varnish as protection against abrasion from UV radiation from the sun
remarks:		
About 95% of all headlamp lenses are currently made from polycarbonate		

The attack of plastic on glass started in the 1980s in North America, continuing in the 1990s in Europe. After a very short time polycarbonate became almost the only material for headlamp lenses. The plastics won through mainly due to their excellent styling freedom. The advantages of glass were neglected. However, the major disadvantage of thermoplastics is temperature resistance. The surface temperature should be lower than 120°C. The polycarbonate lens has to be coated to make the surface abrasion resistant and to protect the base material against UV radiation from the sun. The coatings are thermal or UV hardened (Hilgers, Wiesenberger 2005). It seems that current abrasion resistance is acceptable, but protection against UV radiation from the sun should be improved.

Outlook

The following developments look plausible:

- Reflectors for headlamps:
  The thermoset bulk moulding compound will maintain its position for the next years. Aluminium die cast and steel sheet reflectors will be used for fog lamps and projectors reflectors. Thermoplastics will become more important with new light sources such as high intensity LEDs.
- Lenses for headlamps:
  Polycarbonate will be the dominating material for headlamp lenses. Even new light sources such as high intensity discharge bulbs or high intensity LEDs will not threaten its position. An interesting development could be expected in coating for lenses. Vacuum technology with plasma enhanced polymerisation could bring new opportunities for polycarbonate lenses.
- Tail lamps:
  More and more tail lamps will use LEDs as light source, thus plastic colour filters will no longer be needed.

Spotlight

Thermoset – The plastic that keeps its shape

This spotlight illuminates the choice of materials for the reflector of automotive headlamps. In particular it shows the recipes for thermoset material.

In the history of the automobile two distinct headlamp systems evolved. In America a sealed unit was made entirely of glass. In Europe and Asia a reflector stamped out of sheet metal was varnished for gloss and vacuum metallised with aluminium. Both seemed to fulfil their function adequately. At night the road ahead was illuminated. The reflector was made out of glass or metal and was therefore resistant to temperature and mechanical strain. The reflector kept its shape and thus the optic performance was stable.

Fig. 3.114 Old style sheet metal reflector in parabola shape (source: Visteon) and SAE glass sealed beam

In the 1980's aerodynamic and styling considerations began to change the front of the car significantly. The simple round or rectangular shapes of the typical reflector were in the way. Engineers started to break through the restraints that glass or sheet metal put upon designs. Plastic was the new material of choice for the reflector in the stylish new headlamp. Shown below are examples of more modern reflectors made of thermoset material.

Fig. 3.115 Reflectors from the mid 1980's (left) and from 2000 (source: Visteon) (right)

On the left is a multi-parabolic reflector from the mid-1980's. The nested parabolas are impossible to deep-draw from sheet metal. Notice that the mounting features show that the designer was still thinking in terms of sheet metal. The reflector on the right is from the early 2000's. It holds more than one light source and the actual reflector has a facetted and stepped surface. It is no longer a paraboloid, but a numerically computed free-form reflector. Bulb socket details and attachments are formed with the reflector.

The typical plastics replacing metal or glass in the 1980's were thermoplastic materials. Thermoplastics are huge macromolecules with molecular weights in the millions, created under closely controlled conditions. Only huge chains result from linking the monomers to a polymer. The macromolecules are not cross-linked. Thermoplastic material is like chocolate. It can be moulded into all kinds of shapes. If the cast turns out badly, it can be re-melted and cast again.

Unfortunately thermoplastic material does not work well for headlamp reflectors. The heat from the bulb would deform a reflector made from simple thermoplastic material and distort the precision optic. Glass fibre reinforced plastic due to its anisotropic nature would prevent moulding a precision optic part in the first place.

Fortunately, there are plastic materials which fulfil the requirements for precision reflectors for automotive headlamps. However, these types of plastics do not belong to the generation of plastics which provided the successful materials of the last half century. They are considerably older than thermoplastics; their historical roots are from around 1900.

Already in the 1800's successful attempts were made to duplicate nature's plastics: such as amber or ivory. Those synthetic materials were based on nitro-cellulose, urea and formaldehyde. In the early 1900's the first really successful product for industrial applications was made – a plastic called Bakelite, based on phenol and formaldehyde.

Fig. 3.116 Telephone made of Bakelite.

A typical Bakelite part was created as follows:

- The plastic material provider “cooked” Phenol and formaldehyde into a resin with a viscosity like honey. It was then filled with inorganic fillers and pigments.
- The part maker took this pre-cooked resin “dough”, filled a form with it and “baked” it to its final shape and material properties.

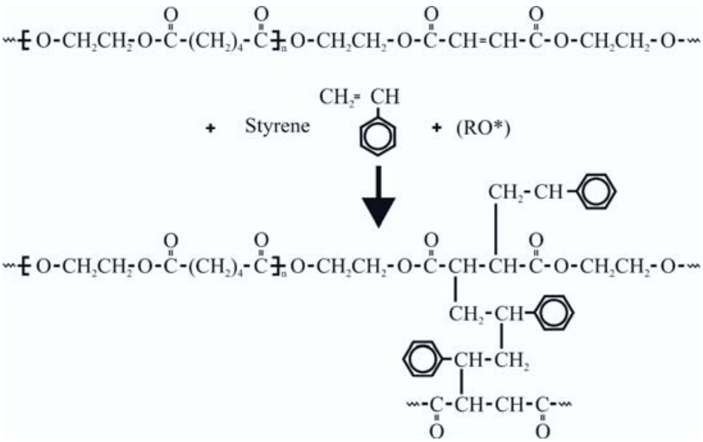


Fig. 3.117 Chemical structure of polyester

In terms of polymer chemistry: the chemical plant produces medium size macromolecules with a molecular weight in the hundreds to low thousands, also called oligomeres. The final part is made by cross-linking these oligomeres to real polymers, macromolecules with molecular weights in the millions. The cross-linking is an exothermal chemical reaction and unlike the moulding of thermoplastic materials, an irreversible process. The cross-linked material is very durable so that the part will keep its shape and does not melt. For this reason this type of plastic is called Thermoset or, in some parts of the world, Duroplast.

For headlamp reflectors un-saturated polyester is used. Polyester of moderate molecular weight (oligomere) containing unsaturated elements (e.g. maleic acid) is cross-linked with styrene under the initiation of radicals (RO*) into a three-dimensional network. The chemical structure shows Fig. 3.117.

Table 3.8 Different material properties

	sheet metal	**glass**	**thermo-set**	**high temp. thermo-plast PEI**	**Al - Die cast**
E-modulus (Mpas)	200,000	75,000	15,000	2,900	74,000
Density (g/cm³)	7.8	2.5	2	1.3	2.6
Thermal upper limit (°C)	>300	>300	200	190	>300
Thermal expansion (E-5/°C)	1.1	0.8	1.8	5.6	2.4
Shrinkage (%)	n.a.	0.8	0	0.7	0.7
Cost index (average reflector size)	n.a	n.a	100	200	250

Application

The ECE beam pattern requires higher precision for the optical system. It should be noted that some of the statements made in this spotlight regarding precision or material requirements are made with the ECE pattern in mind.

As today's headlamps are made for a global market most manufacturers supply lamps for ECE and SAE. Thus, the core optical components are generally made to meet the ECE requirements, which are the most stringent.

A reflector once moulded has to withstand a wide temperature range. First there is the wide range of climates, typically specified at -40 ^{o}C to +120 ^{o}C, in which the head lamp has to perform and second, there is a reflector temperature of 100 ^{o}C – 180 ^{o}C from radiation and convection of the light bulb. Both thermal expansion and the glass transition temperature have to be engineered to avoid distortion and permanent deformation of the reflector.

Table 3.8 illustrates the different material properties which are important for headlamp reflectors.

- Elasticity:
  The first row defines the mechanical properties. The elastic modulus must be high to give stiffness to the reflector in order to withstand mechanical forces such as vibrations.
- Density:
  Overall weight is of great importance in the era of light weight vehicle build; the material's specific density is one of the factors to influence this.
- Thermal limits:
  There is no doubt about the upper thermal limit of the metals and glass. The capability of metals is actually determined by the thermal limit of the metallising base coat. Modern base coats are capable of sustaining temperatures well above 200 ^{o}C.
- Thermal expansion:
  In the time of sheet metal and glass reflectors the thermal expansion was no problem, since steel and glass are well known to perform well in this category. Since most of the specifications regarding headlamp performance are from the time when headlamps were made of sheet metal and glass, the tolerances for thermal expansion are still set high.
- Shrinkage:
  Shrinkage is an important factor when it comes to precision moulding. Materials which only change their shape in the mould, but not their chemical composition, experience shrinkage of around 0.7%. If crystallisation is involved certain materials may even shrink 2%. A thermoset material however, can be formulated to a wide range of shrinkage, most importantly to a very desirable 0% rate.
- Cost:
  For the thermoset material the cost factor is definitely another great selling point beside its technical advantages for the application headlamp reflector.

Moulding of thermoset material is different from moulding of thermoplastic material. Here are some of the more obvious differences:

The typical colours for reflectors made of thermoset material are beige or grey. The manufacturer supplies the "dough" in a 10 kg lump in an airtight plastic bag with a shelf life of several weeks. The injection moulding machine is similar to a standard thermoplastic moulding machine, except the screw/barrel unit is cooled instead of heated, and the mould is heated instead of cooled, in order to start the chemical reaction of cross-linking. The "dough" is force-fed into to the barrel.

Fig. 3.118

The thermoset material for reflectors is often referred to as Bulk Moulding Component (BMC). It is a polyester compound like those typically used for boat repair. Here is the composition:

• Unsaturated polyester in styrene	10-15%
• Zero shrink polymer	5-10%
• Inorganic filler like limestone powder	50-70%
• Glass fibres	10-20%
• Curing catalysts and other additives	< 3%

Unlike the typical polyester compound, BMC contains a finely dispersed thermoplastic resin as an additional "zero shrink" component. This expands during the curing process and thus works against the natural shrinkage which would occur with cross-linking of the polyester. When the eventually cured part cools down, the dispersed zero-shrink resin shrinks to its original shape and leaves microscopic voids within the now solidified reflector. These voids do not have a negative effect on the reflector, but ensure a dimensionally precise reflector.

The "baked" reflector has a matt surface. A clear gloss coating is applied. On top of the coating a thin film of aluminium is deposited to give the reflector a mirror surface.

Outlook

Thermoset material is becoming more and more the material of choice for a design with the specific demands. It excels in the areas of stiffness, heat- and creep resistance, precision moulding, low thermal expansion, cost and other properties which are not found in metal, ceramics or thermoplastics. Among the new applications are car engine components like valve or timing belt covers, fuel cell plates and other under the hood components, where the requirement of extreme dimensional accuracy meet with heat and creep resistance.

Spotlight

Reflective coatings - Mirror surfaces in luminaires

The aim of this spotlight is to reflect on the history of reflective coatings, compare typical applications of coatings used today and provide an outlook to future technologies.

Reflective surfaces have been around as long as luminaires have been used to brighten our environment. The purpose of using reflective surfaces is to maximise the collection of light, direct it and create special effects by modifying the scatter of light rays. Reflective coatings were developed to improve the surface quality of substrates (e.g. reflector surfaces of luminaires) in order to add or modify specific optical properties.

Reflection is defined as the abrupt change in direction of a wave front at an interface between two dissimilar media, so that the wave front returns into the medium from which it originated. Common examples include the reflection of light, sound and water waves. Reflection of light may be specular (i.e. mirror-like) or diffuse (i.e. not retaining the image, only the energy) depending on the nature of the interface (Hentschel 1994). The light reflection index describes the ability of surfaces to reflect light rays.

$$\rho_\upsilon = \Phi_{\upsilon\rho} / \Phi_\upsilon$$

ρ_υ - light reflection index, $\Phi_{\upsilon\rho}$ - reflected luminous flux of light,
Φ_υ - incoming luminous flux of light

Indices for commonly used materials and coatings are charted in public domain literature for luminaire design purpose (Gall 2004). The quality of the reflective layer (measured as appearance quality, reflectivity or photometric consistency) actually starts with the level of gloss and macro-smoothness of the underlying layers, i.e. the substrate or a base coat. Whereas vacuum metallising of aluminium is still the main coating process used in the automotive industry, the majority of domestic luminaires' design is still based on reflectors build from pre-anodised aluminium sheet metal.

History

The development of reflective coating was always influenced by the cost of materials and processes and the increasing need for enhanced optical properties. Already at the end of the 19th century, the effectiveness of luminaires for horse-drawn coaches was improved by using mirrors behind the actual light source, candles or fuel-torch devices. Polished metals made from solid aluminium or brass were used to provide reflectivity.

Fig. 3.119 Coach luminaire using brass reflector (source: Autopal)

Although they were expensive to manufacture, these mirrors provided an efficient way to increase the output of lighting devices.

Historically glass mirrors always represented highly efficient reflective devices. A key benefit of the glass mirror is that the even and smooth surface quality of the glass provides an excellent substrate, good clarity and high reflective ability. On a glass mirror, the reflective coating is applied as a silver nitrate solution, either by pouring or by spraying on the reverse of the glass. This is also called the 2^{nd} surface coating. The glass itself provides a highly scratch resistant protection. The protection for corrosion is accomplished by applying combinations of copper-based and organic topcoats on the silver coating.

From the early stages of headlamp design up to the 1970s, the metal reflector was the reflective luminaire component of choice. The substrates were made from phosphated cold-rolled steel (CRS), or for better corrosion protection, from zinc-plated steel. A sandwich of basecoat, metallised aluminium and topcoat was applied to enhance reflectivity. Specific coating processes were developed for the base-coat and the top-coat to apply even und uniform layers. An example is the "rotational coating" for round reflectors, where the reflector was rotated during spray-coating. Coating fluid viscosity was set to specific tolerances providing "a counter force" to the centrifugal force in order to assure smooth surfaces.

The vacuum metallising technology used for metal reflectors survived as one of today's mainstream processes to create reflective surfaces.

During the 70s and 80s automotive headlamps in North America were designed mainly using sealed beam technology. Sealed beams were manufactured by copying the design of bulbs i.e. sealed glass bodies were formed in the shape of the headlamp using standardised sizes (typically 5.75" round, 5" x 7.87" rectangular).

Fig. 3.120 Sealed beam for automotive headlamp application

The reflective surfaces were created by vacuum metallising of aluminium onto the inner backsides of the beams. The units were sealed after metallising using glass welding.

The 1980s and 1990s marked the arrival of a higher demand for more style-driven looks of the front end of automobiles. The standard size sealed beam unit could not meet this requirement and the development of plastic injection moulded reflectors evolved quickly. The actual reflection coating layers remained similar to the sealed beam approach. However, better corrosion resistance was required because sealing processes became more complex. Additionally headlamp venting systems caused some interfacing of the mirror surface with ambient climate over the life time of a vehicle.

Another well established application is the use of reflective films. Reflective films can be used to increase the reflectivity of garment clothing, traffic signs, side walls of lorries etc. Basically the surface of the film is formed or modified to create micro-optical elements to provide total reflectivity. As an option, reflective coatings can be applied to the film in a continuous process.

When engineers continued to search for more effective ways to create advanced reflective surfaces, the principle of total reflection (TR) provided excellent opportunity for new applications. TR describes an optical phenomenon occurring when light is refracted enough (bent) at a boundary between mediums to send it backwards, effectively reflecting all of the light (Gall 2004). This principle is used by reflector devices with specific optics to reflect the light without using reflective coatings on either boundary surface. Examples are cat's-eyes and reflex areas in automotive rear combination lights. The key benefit of such applications is that no reflective coatings need to be applied, as the surface quality of the substrate itself reflects the light.

Application of reflective coatings

Vacuum metallising is the process of evaporating metals inside a vacuum chamber to create a uniform reflective surface. Pure aluminium (>99.5% purity) is the most commonly used metal for this process. This process is the main choice to create reflective coatings for reflectors of automotive lighting devices e.g. headlamps and rear combination lamps. Newer pre-treatment options enable the application of direct metallising on smooth, unfilled substrates e.g. glass or polycarbonate plastics. Filled substrates e.g. BMC thermoset material, require coating before the reflective layer (base coat) is applied. The coating removes imperfections on the reflector surface.

The application of the actual reflective coating is typically split in five subsequent steps of handling, treatment and depositions:

- Step 1: Loading
  The specimens to be coated are placed in specific fixtures holding the parts in place during the actual coating. Moreover, the fixtures provide the masking of areas to be omitted from coating. The fixtures are mounted on rotating drums (planets) to ensure an equal coating of all surfaces during the process.
  The raw materials for the coating i.e. aluminium solids shaped into to wire hooks, is attached to tungsten wires inside the vacuum coating chamber. The tungsten wires serve as heating elements and induce the actual evaporation.

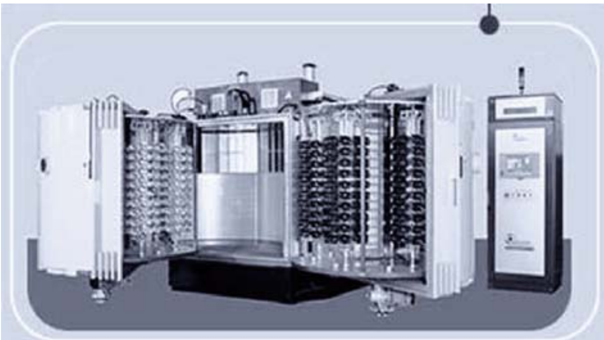


Fig. 3.121 Vacuum metallisation (Arzuffi 2005)

- Step 2: Plasma induced cleaning and activation (Ionic discharge)
  After the initial level of vacuum has been reached, a plasma discharge is initiated by applying a high voltage between two electrodes inside the

vacuum chamber. Active treatment of the coating surface can be accomplished by injecting specific gases, also used to regulate the consistency of the vacuum during the plasma treatment. The treatment activates the surface and enhances the adhesion of the subsequent coating layers.

- Step 3: Vacuum metallising
  After the pre-treatment is concluded, the vacuum is altered to reach the required specific level for the metallisation. Then a high current is led through the tungsten wire, which causes them to react as heating elements transforming the solid aluminium to the physical state of vapour. The aluminium vapour condenses at a regular rate and even distribution on the parts. Because the evaporation is a line-of-sight process, the parts (reflectors) are rotated around the source for complete and selective deposition of the metal. Depending on the final application, a film thickness ranging from 300 to 30,000 Angstroms (1000 Angstrom = 0.1 micrometer) is accomplished.
  Magnetron Sputtering to vaporize reflective coatings is often used as an alternative to aluminium metallisation with heated Tungsten electrodes. Unlike the process described before, the coating is not melted but rather sputtered from the surface of the target (e.g. aluminium). This process is induced by the impact of incoming ions. The use of magnetic fields to enhance the sputtering rate leads to the term "Magnetron Sputtering".

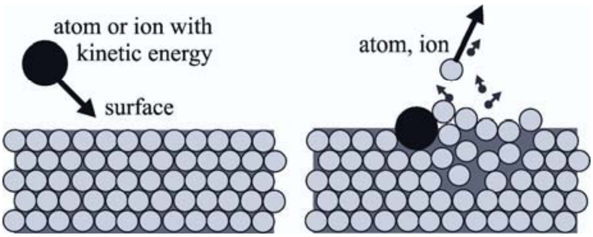


Fig. 3.122 Magnetron Sputtering (Gencoa 2006)

- Step 4: Plasma induced top coating (PECVD-Plasma enhanced chemical vapour deposition)
  Plasma is a special state of matter, the so called fourth state (solid, fluid, gaseous, plasma). It is macroscopically neutral but consists mainly of electrically charged particles. The plasma is formed by electric and magnetic fields. Collisions between neutral particles and energetic electrons generate the ions necessary to perform the plasma coating. When the Silicon monomer is injected into the coating chamber to control the plasma, the energy generated by the plasma causes an equal deposition of atoms and polymerisation of the coating onto the substrate. Such top coats are required to protect the thin aluminium layer from immediate

corrosion addressing typical automotive requirements for surface protection.

- Step 5: Unloading
  Upon completion of the metallising process the chamber is returned to ambient pressure and the reflectors are unloaded.

Another important application for reflective coatings is providing the mirror for domestic lighting luminaries. Just like any lighting device, domestic lighting luminaires make use of reflective surfaces to direct the light or to modify its appearance. Luminaire components with reflective surfaces are reflectors, louvers or shields. Besides the application of plastic reflectors, domestic lighting luminaires make extensive use of aluminium for reflectors and louvers. The surface of aluminium can be mechanically modified to provide a light reflectivity index exceeding 90% e.g. by polishing or by the sequential hot and cold rolling of aluminium coils. As aluminium surfaces are soft and sensitive to corrosion, surface treatments are required.

To create reflective surfaces the aluminium is anodised. Electrochemical brightening and anodising can be applied in batch processes to fixed luminaire parts or continuously to aluminium roll stock. Light reflectivity indices range from 0.80-0.86 for anodised aluminium mirrors.

Fig. 3.123 Industrial continuous coil anodising (Alanod 2005)

Anodised aluminium surfaces can be further enhanced with respect to reflectivity. State-of-the-art processes add 3 layers of vacuum coatings onto the anodised aluminium (Alanod 2005).

- Metallic layer e.g. aluminium or silver
- Clear optical low refractive index layer e.g. metal oxides
- Clear optical high refractive index layer e.g. metal oxides

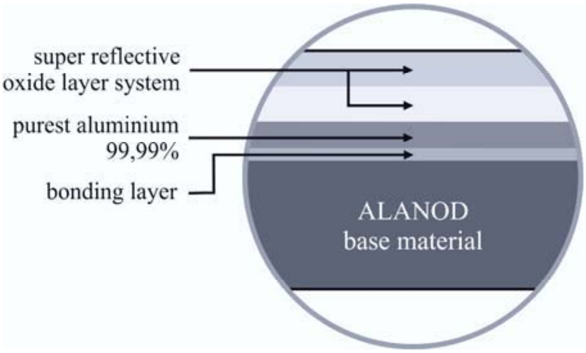


Fig. 3.124 Super-reflective surfaces (Alanod 2005)

The resulting sandwich provides super-reflective surfaces up to light reflective indices of 0.95.

Outlook

The evolution of automotive design requires specific styling-driven new features. Reflective coatings of the future exhibit colour specific properties e.g. by using variable and selective reflectivity indices. The technology of PECVD coating (plasma enhanced chemical vapour deposition) addresses the need for optical coatings for new applications that require very specific properties to pass elevated customer specifications.

The development of highly durable and efficient reflective surfaces creates new applications for innovative products. Examples are products in the spacecraft industry (sun collectors) or energy applications.

Spotlight

Projection lenses for headlamps

The quality of a headlamp’s beam pattern is primarily determined by a few components: the reflector, the bulb, the shutter and the imaging optic. Today many headlamps use an aspheric lens as the imaging optic.

On principle the cut-off line of a projection headlamp is created by the projection of a shutter, which is placed in the focal plane of a projection lens. The shape and the smoothness of the cut-off line depend significantly on the contour and the surface structure of this lens. Thus the lens is a key component of the projection module, which is worth discussing in detail to understand its characteristics and its effect on photometric performance.

History

In 1985 the production of projection headlamps started with several after market lamps. Before that, different concepts for projection systems had been taken into consideration. Multi-lens projection systems like standard systems in imaging projectors were rejected, as well as achromatic ones consisting of at least two spherical lenses to compensate the chromatic aberration of a lens. Ground and polished spherical lenses manufactured in high volumes, were expensive and due to their spherical aberration (Paul 2003) could not be used in single lens projection systems.

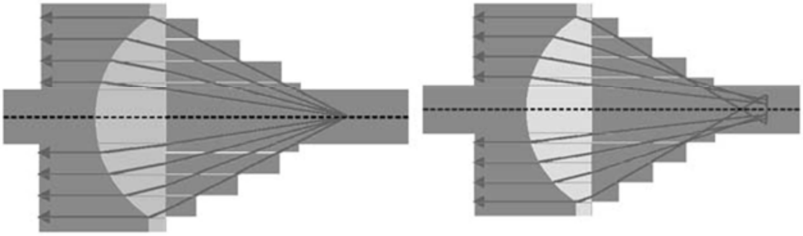


Fig. 3.125 Principle of spherical aberration of a spherical lens (left) and an aspherical lens (right)

Hence, headlamp projection modules were designed to comprise only one aspheric lens.

In order to achieve the cost efficient mass production of large diameter aspheric lenses, the blank moulding process, originally used to manufacture condenser lenses for slide projectors, was adapted to the production of automotive headlamp lenses. This was the breakthrough to a growing market starting with 150,000 lenses in 1985, reaching approximately 30 million. lenses in 2005.

The first lenses were produced from a glass rod, which was heated in a furnace, moulded, annealed, then ground and polished on the planar side. Today however, different types of processes are used. Either liquid glass is injected into multiple moulds, or hot glass is poured into glass moulds and pressed in the next step, or pre-portioned glass drops, so-called gobs, are heated and moulded. The latter process even permits double side moulding, which simultaneously provides two moulded optical surfaces.

Application

The shape of a headlamp lens is determined by the design of the projection module.

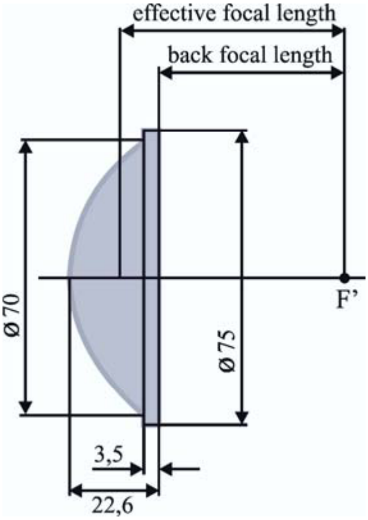


Fig. 3.126 Typical dimensional characteristics of a projection lens

In general the design defines:

- the aspheric diameter
- the (back) focal length, ensuring that the focal plane of the lens meets the shutter, and
- the thickness of the surrounding edge, required to hold the lens tightly in the lens holder.

In order to adapt the photometric pattern of a projection system and to achieve the required appearance, a variety of lens characteristics have to be taken into consideration.

Table 3.9 Characteristics of headlamp lenses

characteristic	functional impact	advantages / potential risks
back focal length (BFL)	installation depth of the projection module	at short back focal lengths, small variations of the distance between lens and shutter as well as of the BFL induce strong variations of the cut-off line as well as the light distribution

characteristic	functional impact	advantages / potential risks
texture on the aspheric side (Holtz 2004)	determines the smoothness of the cut-off line (gradient)	strong textures impede the aiming of the headlamp and may lead to unacceptable glare levels sharp cut-off lines, resulting from clear lenses will not be accepted by car drivers
- frosting (statistical roughness)		+ easy to adjust - hard to control in case lenses are moulded from liquid glass?
- modulation (wave structure)		+ can be directed horizontally and vertically - may lead to a double cut-off line if not controlled properly may induce stripe patterns
- microstructure (fine periodic structure)		+ offers a variety of design potentials ○ in general a microstructure has to be superimposed by a texture - requires an elaborate tooling
surface accuracy	determines the quality and the homogeneity of the photometric pattern	
quality of appearance	as the lens is an element of the headlamp design, defects like bubles, surface flaws, striations and impurities should be kept to a minimum	

Fig. 3.127 Textured lens surfaces; frosting (left), modulation, microstructure (right)

These characteristics describe the aspheric lens in general. Many applications require the integration of functional extensions into the lens. The most important of these extensions are described below.

Colour of the cut-off line

As single lens systems cannot compensate the colour dispersion of glass, blue light is refracted more strongly than red light. Hence the cut-off line in general is not a clear transition from dark to white, but is superimposed with a colour depending on the position of the focal point towards the shutter. This colour can for instance, be compensated for by a cylindrical distortion of the lens, deflecting the colour below the cut-off line where different colours re-mix, resulting in white light.

Overhead signs

In general the current legislation requires that a small portion of the light is deflected to a region between 2° to 4° above the cut-off line, in order to illuminate overhead traffic signs. For this purpose a secondary optic is integrated into the lens.

Fig. 3.128 Secondary sign light optics

Bi-concave / concave-convex lenses

Convex or concave rear sides of a lens may increase the luminous flux or improve the light distribution. Such shapes are realised by moulding the front and the back side of the lens simultaneously. Wave structures, spreading the light horizontally or vertically, can also be integrated into the back side.

Fig. 3.129 Wave structures on the planar side of an aspheric lens

IR reflective coatings

In the case of small installation depths, the planar side of the lens can be coated by an IR reflective coating, in order to protect the outer lens from destruction by IR radiation from the light source (Holtz 2005). This coating reflects a high share of the IR light back to the reflector.

As the lens is a major component for headlamp design, design extensions of lenses have to be considered too.

Freeform shapes

Lenses do not necessarily have to be circular. Almost any shape can be achieved by an appropriate mould design. As advanced moulding processes offer high degrees of design freedom, even the rear side of the lens can be used in order to integrate design features like logos.

Fig. 3.130 Logo integrated into the rear of the lens

Coloured coatings

As the human eye owes its attractiveness and individuality to its colour, the headlamp can attain an individual touch by a coloured daylight design. Such a design can be provided by a reflective dichroic coating on the planar side of the lens, neither affecting the colour of the transmitted light nor the luminous flux.

Outlook

As individual headlamp design requires more and more unique lens design, lens shapes will continue to evolve from circular aspheric shapes to free-form lenses.

Design driven LED headlamps will require a variety of individual lens shapes. Here is a chance for light weight plastic optics, as LEDs do not emit IR light. Thus they do not heat the lens significantly and therefore glass is no longer a requirement. Various freeform optics will be used such as Fresnel lenses, lenses embedding the LED, or array lenses, each of them injection moulded, having sharp and precise features and joining on different levels or a 3-dimensional structure.

This is a big challenge for glass optics, which still offers the advantage of thermal and mechanical resistance and a refractive index independent of the ambient temperature. Multi-array optics or lens designs integrating different light functions, will offer new potentials for ambitious headlamp design.

Fig. 3.131 Lenses for LED applications

3.5 Updating standards

The rules of behaviour for all road users are laid down in the Road Traffic Regulations. If these are not kept, other road users are almost always endangered. It is not so well known however, that there are corresponding regulations for every headlamp or signal lamp. If a manufacturer does not keep to these regulations, its products will not receive certification for use in Europe, while any devices sold in the USA could incur enormous financial burdens as a result of product liability claims. It is therefore, of the utmost importance to know the corresponding regulations and to interpret them correctly.

If in addition, one would like to develop innovative devices, then knowledge of these regulations alone is not enough. Active cooperation in national and international bodies is absolutely essential in order to ensure that legal regulations are adapted or expanded. For every new light source and every new device or new technological development, the corresponding international approval must be obtained. This should guarantee that no matter what changes are made, a signal remains which is as self-explanatory and unambiguous as possible. The figure below shows how the performance of headlamps has been adapted continuously to accommodate the capabilities of emerging technologies.

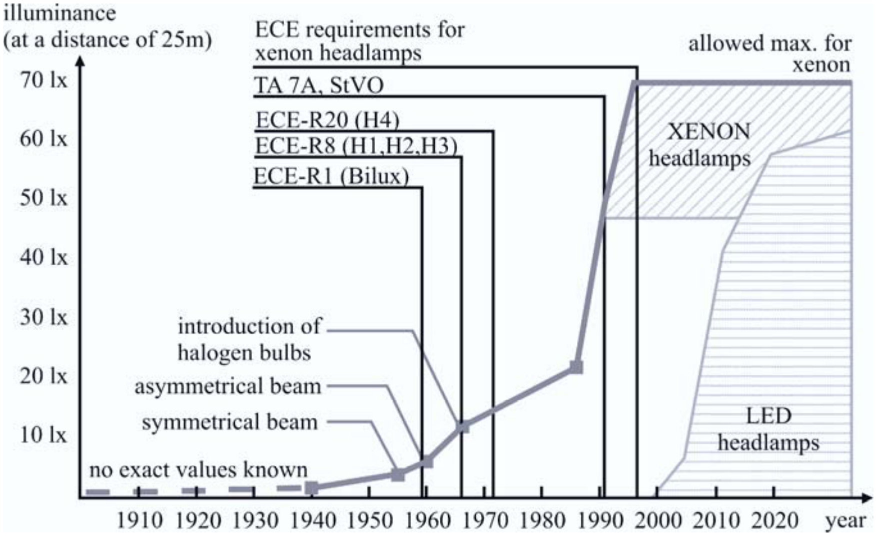


Fig. 3.132 Advancements in headlight performance due to emerging technologies

Regulations and standards often affect the lighting performance. The introduction of xenon light sources into the headlamp required substantial changes in the regulations. It took the industry a fair amount of time and effort to prove that the new technology was available and safe to use in everyday traffic. A similar effort was put into establishing the basis for dynamic headlamps and advanced front lighting systems.

Spotlight

Advanced front lighting reaching approval

Today when driving at night, we usually have only one single dipped beam and main beam distribution for all kind of driving conditions. By means of the newly developed Advanced Front Lighting Systems (AFS) we adopt specific light patterns according to conditions such as weather, speed, and type of road.

The first generation AFS, which has started in 2003, shows headlamps that swivel the light distributions, according to the angle of the steering wheel and speed of the vehicle (Fig. 3.133). Safety improvements with these headlamps have been verified in various surveys (Eureka 1993). Especially in bends and winding roads the detection distance and visibility is enhanced significantly.

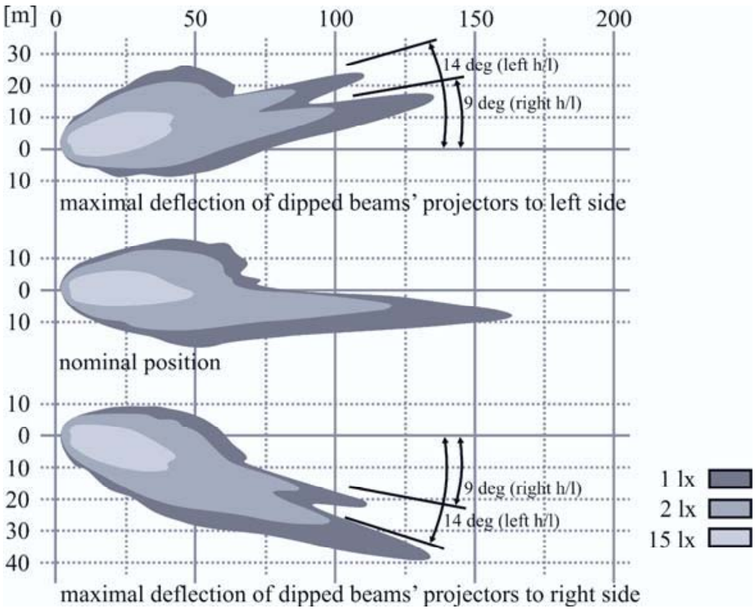


Fig. 3.133 Dynamic bending light

It took nearly a decade until the new regulation regarding front lighting was finalised. In 1992 a group of enthusiastic and safety-conscious light and car manufacturers had finished the introduction of xenon light. The group was expanded to lobby the European legislation with the aim of introducing the advanced lighting system. The research group for Advanced Front lighting Systems (AFS), Eureka project number 1403 was founded. The different concepts for improving light performance when driving at night were evaluated using market surveys conducted in Germany, France, and Sweden for the first time (Eureka 1993).

The surveys indicated a clear ranking of the alternative concepts for improving visibility at night:

- adverse weather light including foggy conditions, followed by
- bending light,
- motorway light and
- town light.

For the motorway light, long range is most important due to the higher speed of the vehicle. For town light long range is not required. Instead the light should illuminate a wide range directly in front of the vehicle. Adverse weather light requires a light which guides the driver without glare for himself or oncoming drivers. The light should also illuminate the sides of the road.

Based on these findings the Eureka group defined and tested dedicated light distributions. The first adaptive light distribution to enter the market was not the top choice from the consumer survey. Instead it was the one requiring least changes in the existing regulations.

Lighting improvement

The AFS system provides an improvement in visibility, especially when driving through bends. A survey (TÜV Rheinland 2003) conducted on a rural road with left and right hand bends, with subjects rating the detection distance when driving with static dipped beam lights produced the following results: The reference standard halogen static dipped beam receives 100% detection distance.

Detection distance improves with the static xenon light up to 123%. The best improvement in obstacle recognition on winding roads is the AFS xenon light at 168%. A very unique halogen dynamic bending light was launched in 2004 (Neumann 2004). Being the only Halogen AFS solution up to now, the improvement of the detection distance is at 155%, very close to the much more sophisticated and more expensive headlamps with xenon light sources.

Table 3.10 Improvements in detection distance with dynamic bending light (AFS)

type	**percent**
halogen standard	100%
xenon standard	123%

AFS halogen	155%
AFS xenon	168%

Safety concerns spark off more general changes in the vehicle. For example, pedestrian fatalities can be reduced by making the front of cars less rigid. Considerable work is now going into the layout of headlamps with respect to reducing the severity of injuries for pedestrians colliding with a car.

Spotlight

Impact behaviour of automotive headlamp

For a long time the impact behaviour of vehicles was focused mainly on the protection of passengers. Big improvements in this field have been achieved over the last few decades. In the meantime however, the protection of pedestrians is being discussed ever more. In 2003 the European Parliament and Council adopted the regulation No. 2003/102/ES for the protection of pedestrians and other exposed road users.

On the other hand, there is still a high pressure on engineers to decrease the costs for repair after a vehicle's crash at lower speeds. Damage assessment tests are conducted in many countries, to determine the insurance classification, the repair costs incurred due to restraint system deployment and associated damage. Results of low speed impact tests are usually taken into account and reflected in the insurance classification of the vehicle.

Based on the above criteria the design of the vehicle front-end is becoming an important contributor to meeting requirements for pedestrian protection and protection for low speed impact. The design of automotive headlamps has to take into account the new criteria.

Pedestrian impact requirements

To meet the legislative criteria, four specific impact tests have been defined. They determine the required level of pedestrian protection for each passenger car. The tests are based on the recommendation of the European Enhanced Vehicle Safety Committee (EEVC), and they are performed by crashing the vehicle into specified impactors. The first two tests are a valid requirement from 2005 in the first phase of the implementation of pedestrian protection:

- Adult head impact on the bonnet and windshield surface
- Upper leg and pelvis form impact on the bonnet leading edge

- Lower leg impact on the front bumper
- Child head impact on the bonnet surface

Fig. 3.134 Difference in front-end styling – older sharp design with ordinary shape of headlamp design (left) and new smooth styling of front-end with shaped headlamps (right)

The tests for upper leg and the child head impact are particularly relevant to the design of headlamps.

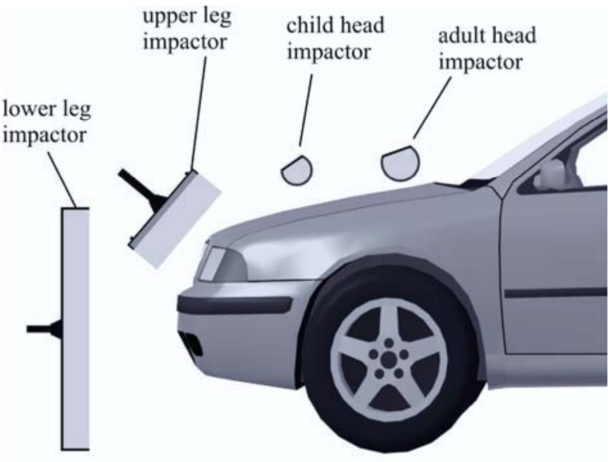


Fig. 3.135 Impact zones defined for pedestrian protection testing

Impact to the upper leg and headlamp's behaviour

This type of the impact test is mainly aimed at the leading edge of the bonnet. The displacement of the front portion of the headlamp during the impact has to follow the front-end behaviour.

Table 3.11 Performance criteria for impact to upper leg

upper leg form		
phase of implementation	**phase 1**	**phase 2**
impactor Mass (kg)	9,5	9,5
testing area	bonnet leading edge (SUV bumper)	bonnet leading edge (SUV bumper
required impact velocity (mps/kph)	11,1 / 40	11,1 / 40
sum of impact forces limit (kN)	5 (bonnet) 7,5 (bumper)	5
bending moment limit (Nm)	300 (bonnet) 500 (bumper)	300

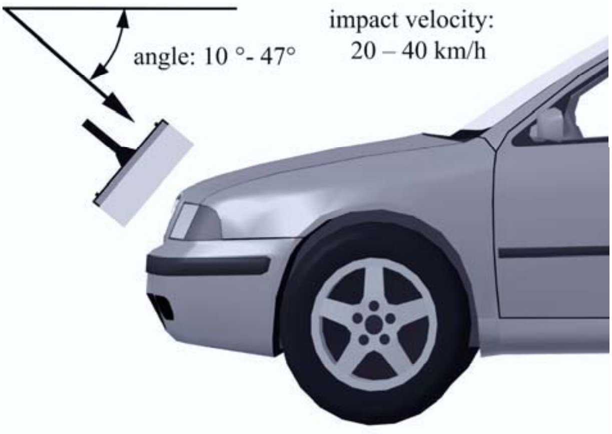


Fig. 3.136 Impact to upper leg – description of the test and performance criteria

The performance criteria limit the maximum forces and momentum during energy absorption of the headlamp. Note that in a second phase of the implementation the limits will be further tightened.

To meet these criteria and to absorb impact energy as smoothly as possible, it is necessary to utilise any compressible behaviour of the headlamp itself and to use the space under and behind the headlamp. Solutions using special mounting systems for the headlamp will play a significant role.

Table3.12 Performance criteria for impact to child head

child head form		
phase of implementation	**phase 1**	**phase 2**
impactor mass (kg)	3,5	2,5
testing area	bonnet	bonnet
required impact velocity (mps/kph)	9,7 / 350	11,1 / 40
head injury criterion limit (HIC)	1000 - 2/3 2000 - 1/3	1000

Impact of the child head and headlamp's behaviour

Generally three areas of child head impact are taken into account:

- Impact directly on the upper portion of the headlamp's front lens
- Impact on the gap between the headlamp's front lens and the bonnet
- Impact on the bonnet or fender portion, located just behind the headlamp

The headlamp has to absorb energy, while the front lens area should follow the displacement of bonnet and bumper to avoid the creation of sharp edges during the impact. The front-end design should allow space between the bonnet and the headlamp envelope for smooth energy absorption.

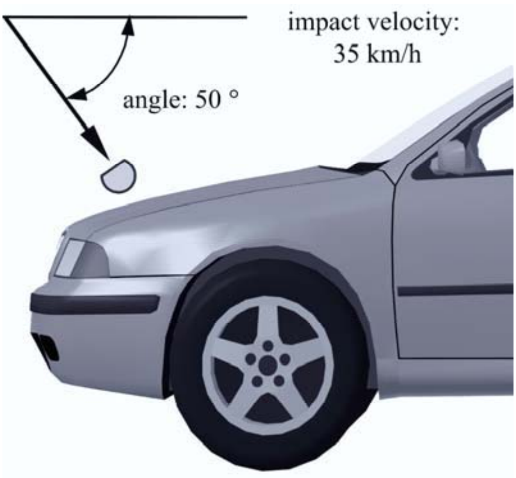


Fig. 3.137 Impact to child head – description of the test and performance criteria

Outlook

Headlamp design will change significantly with the introduction of phase 2 of the pedestrian protection regulation. The position of attachments and mounting point will have to be revised using crash simulations. Rupture lines will have to be designed into mounting brackets to limit forces and allow free movement. If the headlamp has space to tilt and drop backwards on impact, then the impact forces can be limited more easily. The forces exerted by the headlamp lens can be reduced further by using special flexible material, which can even snap back into shape after impact. Heavy projector systems with glass lenses might have to be moved further back within the headlamp structure.

Spotlight

Guidelines for visibility and mounting requirements (SAE)

This spotlight provides the reader with guidelines on the legally required functions. It illustrates the complexity of the requirements for vehicle lights, by looking at the prescriptions for the visibility and mounting of lights on a motor vehicle. This spotlight concentrates only on the legal requirement within the group of countries subscribing to SAE. There are some slight variations for the ECE market which are not specifically mentioned in this section. (For additional information the reader should refer to the specific ECE Lighting Requirements.) Please also note that regulations are altered from time to time. Therefore the guidelines below cannot cover every situation that may occur for all lighting devices on vehicles. The majority of the information presented has been compiled from the MVSS108 SAE Lighting Requirements. For reasons of consistency with the regulations, the spotlight uses the American terminology for lighting devices, for example the ‘indicator’ becomes the ‘turn signal’, the ‘dipped beam’ becomes the ‘passing beam’.

Visibility and mounting guidelines

Front turn signal

The front turn signal is usually combined with front park function. The illuminated colour must be amber.

- Area: 2200 mm^2 (3½ in^2) per lamp for turn signal (effective or “flat” lens area only; curved lenses require more total area).
- Visibility: (a) Turn signal filament must be unobstructed through 45° outboard of vehicle to 20° inboard and from 15° up to 15° down. Note: in order to be considered visible, 2 in^2 (1300 mm^2) must be visible at 45°

or (b) the lamp must provide a luminous intensity of not less than 0.3 cd throughout the photometric pattern defined by the corner points that define the lit edge of the lamp. That is 15° above horizontal, 45° inward, and 80° outward, to 15° below horizontal, 45° inward, and 80° outward. Note: the downward angle may be reduced to 5° if the lower lighted edge of the lamp is less than 750 mm above the ground.

Table 3.13

	β_1	β_2
Front fog	45°	10°
Front turn	80°	45°

- Mounting: Minimum of 380 mm (15 in.) and max 2110 mm (83 in.) above road surface to centre of lamp with vehicle at curb weight, and “as far apart as practicable.”
- Minimum intensity at optical axis: 200 cd for turn (500 cd if < 4 in. requirement below is not met – see next paragraph).

Additional Information: If the turn bulb filament is less than 100 mm (4 in.) from the edge of the low beam headlamp, photometric requirements are 250% of normal. Follow SAE chart for incremental change between 60 and 100 mm.

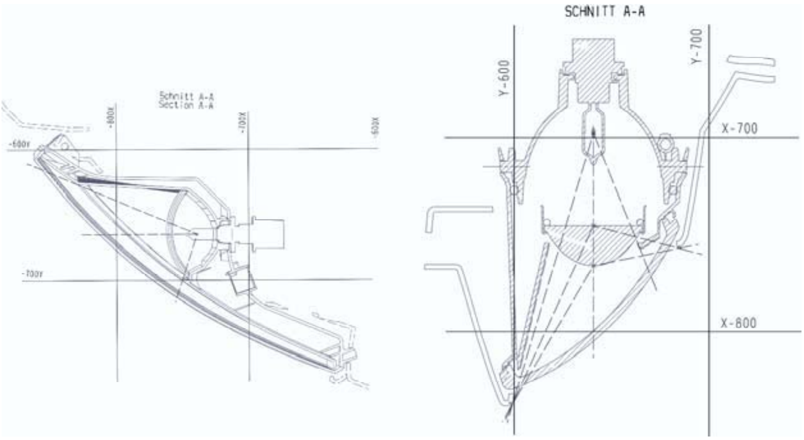


Fig. 3.138 Front fog (right) and turn lamp (left) – Horizontal sections A-A

Front park

The front park signal is usually optically combined with front turn: illuminated colour must be amber. The signal may also be clear with an amber bulb.

- Area: No requirement for park lamp.
- Visibility: (a) Park lamp filament must be unobstructed through 20° inboard to 45° outboard, and 15° up/down. Note: to be considered visible, 2 in² (1300 mm²) must be visible at 45°, or (b) the lamp must provide a luminous intensity of not less than 0.05 cd throughout the photometric pattern defined by the corner points that define the lit edge of the lamp. That is 15° above horizontal, 45° inward, and 80° outward, to 15° below horizontal, 45° inward, and 80° outward. Note: the downward angle may be reduced to 5° if the lower lighted edge of the lamp is less than 750 mm above the ground.
- Mounting: Minimum of 380 mm (15 in.) and max 2110 mm (83 in.) above road surface to centre of lamp with vehicle at curb weight, and “as far apart as practicable.” Minimum intensity at optical axis –min. 4 cd for park; max is 125 cd.

Rear turn signal (amber or red)

- Area: 5000 mm² (8 in²) per lamp for turn signal (effective, or “flat” lens area only; curved lenses will require more total area). Recommended current SAE shows 3750 mm² min area.
- Visibility: (a) Turn signal filament must be unobstructed through 45° outboard of vehicle to 20° inboard, and from 15° up to 15° down. Note: to be considered visible, 2 in² (1300 mm²) must be visible at 45°, or (b) the lamp must provide a luminous intensity not less than 0.3 cd throughout the photometric pattern defined by the corner points specified in SAE chart Fig. 3.138. That is 15° above horizontal, 45° inward, and 80° outward, to, 15° below horizontal, 45° inward, and 80° outward. The downward angle may be reduced to 5° if the lower lighted edge of the lamp is less than 750 mm above the ground.
- Mounting: minimum of 380 mm (15 in.) above road surface to centre of lamp with vehicle at curb weight, and “as far apart as practicable.” Minimum intensity at optical axis – 80 cd (red); 130 cd (amber) – single cavity 95 cd (red); 150 cd (amber) – double cavity. Note: amber values differ from SAE recommendation.

Additional Information: If turn indicator is combined with tail or parking lamps, then the turn indicator shall not be less than three times the luminous intensity of these lamps on or above the horizon. If multiple compartment lamp or multiple lamps are used and the distance between adjacent lamps does not exceed 560 mm for two lamps and 410 mm for three lamps, then an increasing photometric requirement exists. Refer to Table 3.13 in SAE manual under subject topic.

Additional Information - on trucks, lighting device shall not be obstructed by tail gate in down position.

Tail and stop lamp (normally optically combined; colour must be red)

- Area: 5000 mm² (8 in²) per side for stop lamp (effective, or "flat" lens area only; curved lenses require more total area). No specific area requirement for tail lamp.
- Visibility: (a) filament must be unobstructed through 45° outboard of vehicle to 20° inboard, and from 15° up to 15° down. Note: to be considered visible, 2 in² (1300 mm²) must be visible at 45°, or (b) the lamp must provide a luminous intensity not less than 0.05 cd throughout the photometric pattern defined by the corner points specified in SAE chart Fig. 3.139. That is 15° above horizontal, 45° inward, and 80° outward, to 15°below horizontal, 45° inward, and 80° outward. The downward angle may be reduced to 5° if the lower lighted edge of the lamp is less than 750 mm above the ground.
- Mounting: minimum of 380 mm (15 in.) above road surface to centre of lamp with vehicle at curb weight, and "as far apart as practicable." Minimum intensity at optical axis – 2.0 cd (tail); 80 cd (stop) – single cavity 3.5 cd (tail); 95 cd (stop) – double cavity.

Additional Information - on trucks, shall not be obstructed by tail gate in down position.

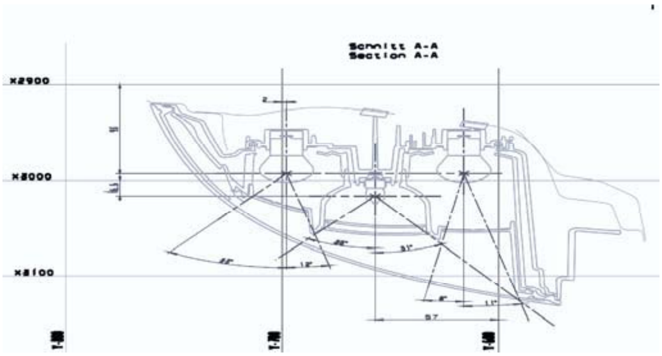


Fig. 3.139 Rear combination lamp – Horizontal section A-A

Side marker lamps (front must be amber; rear must be red)

- Area: minimum recommended lens opening is 13 mm high x 30 mm long (0.5 in x 1.25 in, 0.625 in²). Lamp geometry will determine actual size requirement.
- Visibility: front marker - 10° up and 10° down, 45° to front, and 35° to rear; rear marker - 10° up and 10° down, 45° to rear, and 35° to front. Note: actual inboard test angle may be less than 35° per layout check.
- Mounting: Minimum of 380 mm (15 in.) above road surface to centre of lamp with vehicle at curb weight. Front marker must be as far forward as practicable and rear marker must be as far rearward as practicable.
- Minimum intensity at optical axis: 0.25 cd (red) 0.62 cd (amber).

Additional Information: may be combined with park and turn lamp (front) or tail lamp (rear); if separate lamp, usually combined with side reflex.

Back up lamps (white, one or two required)

- Area: (a) integral with tail lamp, or two lamp system. 3870 mm² (6 in²) for vertical lamp, or 3225 mm² (5 in²) for horizontal lamp ("flat" lens area only). (b) One lamp system. 6450 mm² (10 in²) recommended for horizontal lamp, and 7740 mm² (12 in²) for a vertical lamp ("flat" lens area only). Note: no specific legal area requirements needed to be met. Visibility: one lens centre must be visible at any point in a vertical plane 900 mm (3 ft.) to rear of vehicle, extending 600 mm to 1800 mm (2 to 6 ft.) above the ground, and 900 mm (3 ft.) out to each side of the vehicle. Photometric test angles require each lamp to be free of obstructions from 45° left and right, and from 10° up to 5° down.
- Mounting: no specific requirement as long as visibility and photometric criteria are met.
- Minimum intensity at optical axis: 80 cd (Maximum above horizontal is 300 cd).

Additional Information: (a) one-lamp systems require double the output of each lamp in a two-lamp system. (b) Asymmetrical left hand and right hand lamp output must be added together at each test point to ensure total output is double that of a single lamp. (c) Non-white light output must be "incidental", usually accepted when not exceeding 20%.

Reflex reflectors

Rear reflex – required on rear of vehicle on each side of vehicle centreline; the colour must be red.

Side reflex – required on each side of vehicle both forward and rearward; forward reflex must be amber, and rearward reflex must be red.

- Area: must be determined based on construction and shape of lamp. 2905 mm² (4.5 in²) is usually recommended for applications where reflex is integral with a side marker or by itself. 3225mm² (5.0 in²) is recommended for applications integral with tail lamp or park lamp. If surface is curved and/or mounting angles are skewed, more area will be required.
- Visibility: unobstructed when viewed from all angles from 20° left to 20° right, and from 10° up to 10° down. 90% of the 10 in. circle must be visible at the extremes.
- Photometric: Photometry values will be that of Table 3.13 in SAE manual for red reflex, amber reflex will be 2.5 times this value and white reflex will be 4 times this value. Minimum intensity at 0° will be 420 mcd.
- Mounting side reflex: centre of reflex must be a minimum of 380mm (15 in.) above road surface with vehicle at curb weight. Amber must be as far forward as practicable, and red must be as far rearward as practicable.
- Mounting rear reflex: centre must be at least 380mm above road surface. Must be on each side of vehicle centreline, at same height, and as far apart as practicable.

Additional Information: There are no maximum area specifications. However, only 7740 mm² (12 in²) contained within a 254 mm (10 in.) diameter circle may be used to meet photometric requirements. Homologation Note: - side reflectors are not permitted on European vehicles.

Centre high-mounted stop lamp (CHMSL)

- Area: 4.5 in² (2900 mm²) minimum effective projected area, on a flat plane.
- Visibility: unobstructed from 45° left to right, 10° up to 5° down. (No specific lens area, so any portion of signal can be visible; however, photometric values must be met from 10° left to right, and from 5° down to 10° up). Light must be red.
- Minimum intensity at optical axis: 25 cd and maximum of 130 cd.
- Mounting: on vehicle centreline, either interior or exterior; may be mounted to glass. If mounted below the rear window, no portion of lens shall be more than 3 in. from bottom edge of glass (6 in. for convertibles)

Additional Information: (a) internal lamp must be designed in a way to minimise glare light/reflections in the rear window visible to the driver either directly or indirectly reflected in the rear view mirror. (b) convenient bulb replacement without special tools is required; multiple cavities are permissible. (c) CHMSL will not be combined with any other lamp or reflective device other than with a cargo lamp. (d) internal lamp must allow cleaning of rear window.

Homologation Note - if multiple cavities, then lamp must pass photometric testing with each of the bulbs not functioning, testing one at a time. In other words, if 3 bulb system, must pass with left bulb burned out and remaining two functioning, then also test with centre bulb out and remaining two functioning and then again with right bulb out and remaining two functioning.

License lamps

White, one or two required - either two on sides of plate or one on centre over the plate.

- Area: no requirement.
- Visibility: no white light allowed to rear of vehicle.
- Photometric: measured on a simulated license plate, the luminance intensity shall be 2.0 cd/m² and the ratio of max. to min. measurement at the test locations shall not exceed 30/1 for automotive and 25/1 for motorcycle.
- Mounting: (a) plate angle – 15° or less from vertical; (b) incident light angle – 8° minimum from edge of light emitting surface to the furthest point designed to be illuminated by that lamp; (c) bulb filament at least 25 mm (1 in.) from plane of plate; (d) top or side mounting is recommended.

Headlamps

The headlamps may be round or rectangular, 2 or 4 lamp sealed beam systems, or 2 or 4 lamp aerodynamic lamp systems.

- Area: no requirement.
- Visibility: the horizontal cut-off angle outboard of the outside unit focal point shall be a minimum of 45°; the downward vertical cut off angle must be unobstructed through 45°; no protrusions, such as nosepieces, are permitted within 9½ inches of either aiming plane for small round headlamps, and 10½ inches for all others (for split image/aimer alignment).
- Mounting: (a) the lamp centres must be a minimum of 559 mm (22 in.) from the road surface with the vehicle at curb weight, and "as far apart as practicable"; (b) 4-lamp systems may be either vertically stacked or side-by-side.

Additional Information: a) there must be sufficient clearance around the headlamp to install mechanical aimers and aim without removing any parts, such as bezels or mouldings; (b) when in operation, no covers or obstructions are permitted; (c) an 8° screw driver access angle is recommended for adjustment around each adjusting screw.

Note: aerodynamic headlamp requirements are extensive and beyond the scope of this article. Therefore they will not be summarised here.

Table 3.14

	β_1	β_2
Low (or passing) beam	46°	10°
High (or main) beam	6°	6°
Position lamp	80°	46°

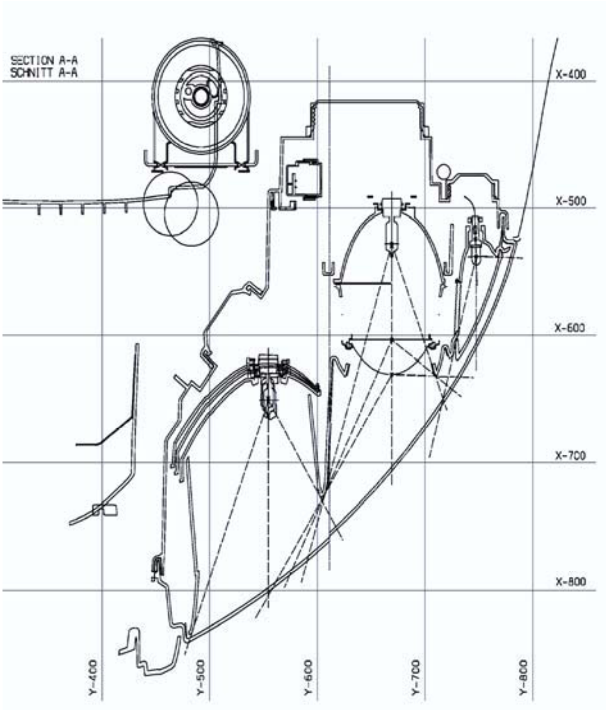


Fig. 3.140 Headlamp – Horizontal section A-A

Front cornering lamp (FCL)

Must be a white or yellow steady burn lamp used in conjunction with the turn signal to supplement the headlamp, illuminating in the direction of the turn. FCL may also be used independently of turn to ease manoeuvrability of vehicle at slow speeds.

- Area: No specific area requirement for FCL.

- Visibility: No visibility requirements are listed, although photometric test points follow range from 45° rearward to 85° forward and 2.5° down to 90° up. These angles are calculated perpendicular to the longitudinal axis of the vehicle.
- Mounting: minimum of 305 mm, and maximum of 760 mm, above road surface to centre of lamp with vehicle at curb weight.

Minimum intensity at optical axis: 500 cd.

Additional Information: To be activated only when headlamps are operational.

General requirements (all lighting components)

All lamps must be securely mounted on rigid parts of the vehicle <u>not</u> designed to be removed except for repair.

If equipment such as mirrors or snowploughs prevents photometric compliance, auxiliary lighting devices are required.

Left side and right side lighting devices must be equidistant from the vehicle centreline and at the same height. For example, the left side parking lamp must be the same distance from the ground as the right side parking lamp, and the same distance from the centre of the bumper or grille.

All height requirements are to be measured from the ground to the optical centre of the lamp (normally the focal point of bulb projected on the lens), with the vehicle at curb weight, and with the minimum size required (MSR) tyre.

Most of the values referenced are the limits for legal requirements. Actual design practice should provide for enough safety margins to accommodate for any variations in the part built.

4 Fundamental Problems with Automotive Lighting

Automotive lighting practice is becoming more sophisticated in both its ambitions and its technology. However, two fundamental problems remain that have dogged automotive lighting from its earliest days:

- At low light levels, such as occur after dark, the response of the human visual system to different wavelengths is not the same as the response at high light levels i.e. during daytime. Yet all the photometric measurements associated with the specification and design of automotive lighting assume the daytime response of the visual system.
- The easiest way to reveal the road ahead is to project a lot of light along it. The problem is that such an approach dazzles drivers coming the other way, reducing their view of the road and causing discomfort. Striking the necessary balance between visibility and glare has been a perpetual problem for the regulation and design of automotive lighting

This chapter will discuss the nature of both these problems and consider some possible solutions.

4.1 Mesopic vision

4.1.1 Mesopic vision – The problem

For all the photometric quantities used in the measurement of lighting, the conversion from radiometric units to photometric units is made using the CIE Standard Photopic Observer. This is a continuous approximation to the brightness response of the fovea at modest light levels (Viikari et al 2006). The use of the CIE Standard Photopic Observer for all light measurement poses a problem for automotive lighting, because as light level is reduced, different photoreceptors are active in different parts of the retina. Specifically, as the adaptation luminance falls below about 3 cd/m^2, the rod photoreceptors escape the grip of the cone photoreceptors and begin to become influential. Their influence continues to grow until as the adaptation luminance falls below about 0.001 cd/m^2, at which point the cone photoreceptors cease to function, the rod photoreceptors are all that are left to serve vision. Vision where both cone and rod photoreceptors are active is called mesopic vision.

As a consequence of the existence of mesopic vision, the spectral sensitivity of the visual system changes variously for different parts of the retina. Ironically enough, for the fovea there is no change. The CIE Standard Photopic Observer still applies to the fovea in the mesopic range, because medium and long wavelength cones predominate in the fovea, which is what the CIE Standard Photopic Observer is based on. However, in the rest of the visual field, the spectral sensitivity is in a state of continual change, as the balance between rod and cone photoreceptors changes with light level and eccentricity, until either rods dominate, as in scotopic vision, or cones dominate as in photopic vision.

Mesopic vision is important for automotive lighting because the lighting conditions produced by headlights and by road lighting tend to straddle the mesopic / photopic boundary. Nonetheless, all the photometric quantities that are used to characterise automotive lighting use the CIE Standard Photopic Observer. In theory, this practice can lead to situations where the photometric measurements bear little relation to the visual effect of the light source.

Whereas the CIE has produced recommendations for the spectral response of the fovea in the photopic state, the CIE Standard Photopic Observer, (and for a much larger area in the scotopic state, the CIE Standard Scotopic Observer), it has not been able to develop a system of mesopic photometry. This is not for want of trying (CIE 1989). Indeed several different systems have been suggested, most using the perception of brightness as a criterion and based on some weighted combination of photopic and scotopic measurements, to achieve a transition from the Standard Photopic Observer to the Standard Scotopic Observer. Others have abandoned the perception of brightness as the quantitative measure of visual effect, and using reaction time, have developed a comprehensive system of photometry that covers photopic, mesopic and scotopic light levels (Rea et al 2004).

Until the CIE is able to achieve international agreement on a system of mesopic photometry, the Standard Photopic Observer will continue to be used for light measurements relevant to automotive lighting and may mislead in some situations.

4.1.2 Performance in mesopic vision

Laboratory studies

The simplest place to start this discussion of the impact of mesopic vision is in the laboratory where the visual field can be lit uniformly to the same luminance, with light of the same spectrum. He et al. (1997) carried out such a laboratory experiment in which high pressure sodium and metal halide light sources were compared for their effects on the reaction time to the onset of an achromatic 2° disc, either on axis or 15° off-axis, for a range of photopic luminances from 0.003 cd/m^2 to 10 cd/m^2. The luminance contrast of the disc against the background was constant at 0.7. Fig. 4.1 shows the median reaction time to the onset of the stimulus, on-axis and off-axis, for a range of photopic luminances, for two experienced subjects. From Fig. 4.1 it is evident that reaction time increases as photopic luminance decreases from the photopic to the mesopic state, for both on-axis and off-axis detection. There is no difference between the two light sources in the change of reaction time with luminance for on-axis detection. But for off-axis detection, the reaction times for the two light sources begin to diverge as vision enters the mesopic region. Specifically, the reaction time is shorter for the metal halide lamp at the same photopic luminance, and the magnitude of the divergence between the two sources, increases as the photopic luminance decreases.

These findings can be explained by the structure of the retina. The fovea, used for on-axis vision, contains only cone photoreceptors, so its spectral sensitivity does not change as adaptation luminance decreases until the scotopic state is reached. At this point the fovea is effectively blind. The rest of the retina contains both cone and rod photoreceptors. In the photopic state the cones are dominant but as the mesopic state is reached the rods begin to have an impact on spectral sensitivity, until in the scotopic state the rods are completely dominant. Given the different balances between rod and cone photoreceptors in different parts of the retina and under different amounts of light, it should not be surprising that the metal halide lamp produces shorter reaction times for off-axis detection than the high pressure sodium lamp in the mesopic range.

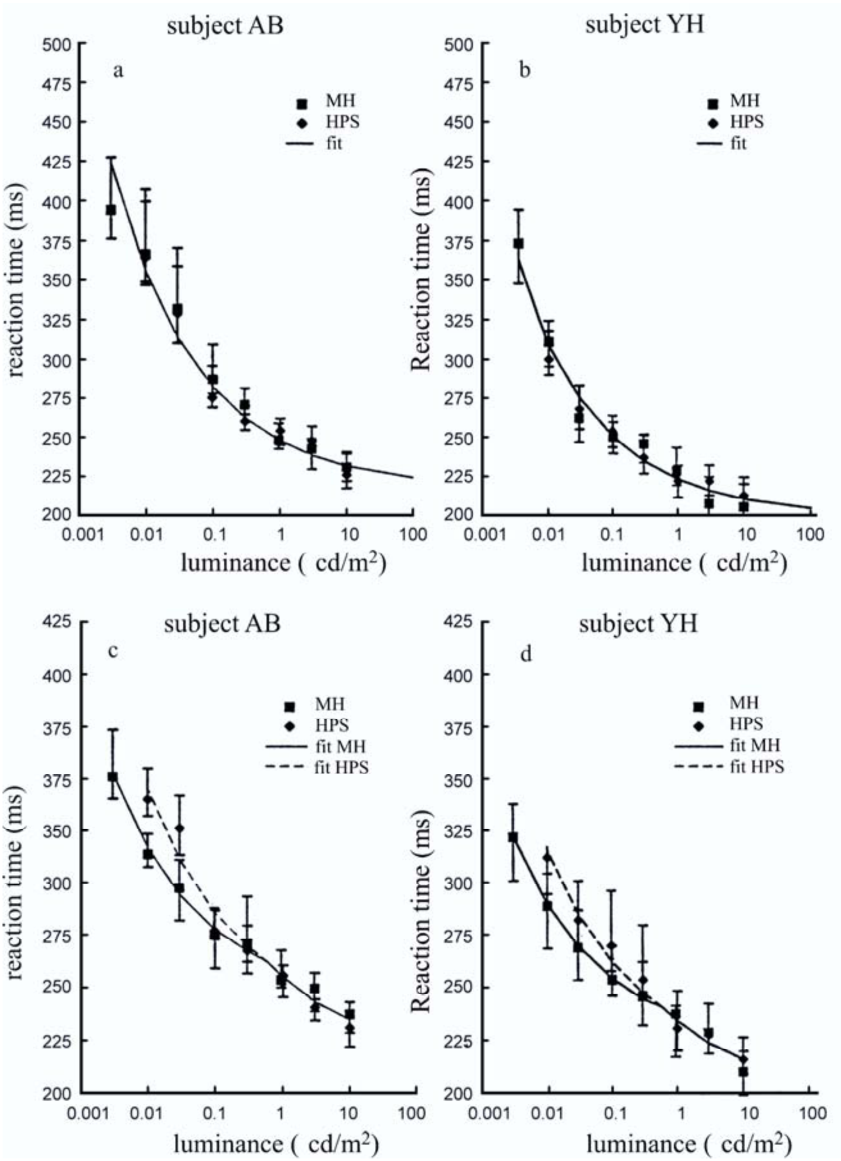


Fig. 4.1 Median reaction times, and the associated interquartile ranges, to the onset of a 2°, high contrast target seen either (a and b) on -axis or (c and d) 15° off-axis, and illuminated using either high pressure sodium (HPS) or metal halide (MH) light sources, for photopic luminances in the range 0.003 to 10 cd/m^2 (after He et al 1997)

This is because the spectral power distribution of the metal halide lamp is more effective in stimulating rod photoreceptors. It is also evident why there is no difference between the two light sources for on-axis reaction times.

Lewis (1999) has obtained similar results using illuminated tranparencies. Fig. 4.2 shows the mean reaction time to correctly identify the vertical or horizontal orientation of a large achromatic high contrast 13° by 10° grating, where the grating was lit by one of five different light sources used for road lighting: low pressure sodium, high pressure sodium, mercury vapour, incandescent and metal halide. Mean reaction time was plotted against photopic luminance. As long as the visual system is in the photopic range, there is no difference between the different light sources, provided they produce the same photopic luminance. However, when the visual system is in the mesopic state, then the different light sources produce different reaction times. The light sources that better stimulate the rod photoreceptors (incandescent, mercury vapour and metal halide) gave shorter reaction times than the light sources that stimulate the rod photoreceptors less (low and high pressure sodium).

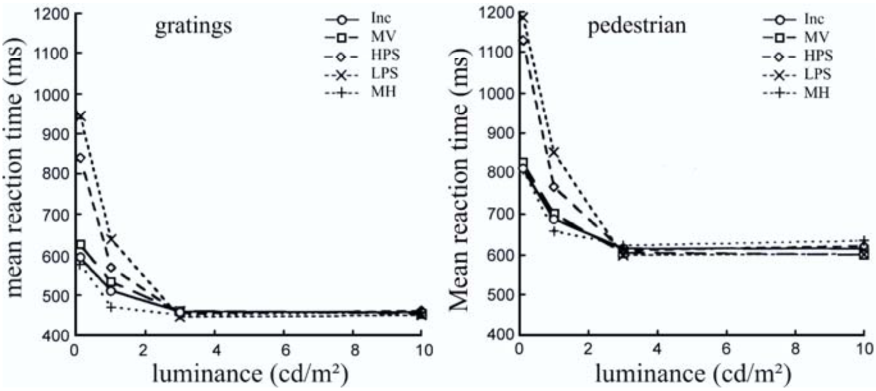


Fig. 4.2 Mean time to correctly identify the vertical or horizontal orientation of a grating and to identify the direction a pedestrian located adjacent to a roadway is facing, plotted against the photopic luminance produced by five different light sources (Inc = incandescent, MV = mercury vapour, HPS = high pressure sodium, LPS = low pressure sodium, MH = metal halide) (after Lewis 1999)

Lewis (1999) used the same technique to examine the effect of the spectral power distribution of a light source on the time taken to extract information of relevance to driving. In this case, the transparency showed a woman standing at the right side of a road in the presence of trees and a wooden fence. In one transparency the woman was facing towards the road, in the other she was facing away from the road. The subject's task was to identify which way the woman was facing. Fig. 4.2 also shows the mean reaction times for this task, under the different light sources and for a range of photopic luminances. Again, there is no difference between the light sources as long as the visual system is in the photopic state. But once it reaches the mesopic state, the light sources that more effectively stimulate the rod photoreceptors produce faster reaction times.

Another approach to evaluating the effect of light spectrum in mesopic conditions measured the probability of detecting the presence of a target off-axis. Bullough and Rea (2000) used a simple driving simulator based on the projected image of a road, controlled by computer software. The subject could control the speed and direction of the vehicle along the road with a steering wheel and accelerator. A computer monitored the time taken to complete the course and the number of crashes occurring. Filters were applied to the projected image of the course to simulate the light spectrum of both high-pressure sodium and metal halide lighting and more extreme red and blue light, for a range of luminances. Interestingly, there was no effect of light spectrum on the time taken to complete the course, i.e. on driving speed, but there was a marked effect on the ability to detect the presence of a target near the edge of the roadway. The light spectra that more effectively stimulated the rod photoreceptors (blue and metal halide) led to a greater probability of detection than light spectra that did not stimulate the rod photoreceptors so effectively (red and high pressure sodium).

Field studies

The laboratory studies discussed above leave little doubt that, for detecting off-axis targets, using light sources that more effectively stimulate the rod photoreceptors is advantageous when the visual system in the mesopic state. But is the advantage retained in the field where both luminances are much less uniform? Akashi and Rea (2001a) had people drive a car along a short road while measuring their reaction time to the onset of targets 15° and 23° off-axis. The lighting of the road and the area around it was provided either by high-pressure sodium or metal halide road lighting, adjusted to give a similar amount and distribution of light on the road, and seen with and without the vehicle's halogen headlights on dipped beam. There was a statistically significant difference between the high-pressure sodium and metal halide lighting conditions but no statistically significant effect of the halogen headlights. Specifically, the mean reaction time to the onset of the targets was shorter for the metal halide lighting than for the high-pressure sodium lighting at both eccentricities (Fig. 4.3).

Using the same experimental site and equipment, Akashi and Rea (2001b) also examined the effect of disability glare caused by halogen headlights from a stationary car in the adjacent lane, on the ability of a stationery driver to detect off-axis targets at 15° and 23° when the road lighting was provided by metal halide and high pressure sodium lighting. Again, the mean reaction times to the onset of the targets were longer for the high-pressure sodium road lighting than for the metal halide road lighting, by about 4%. As might be expected, the mean reaction times were longer when the headlights in the opposing vehicle were switched on, also by about 4%.

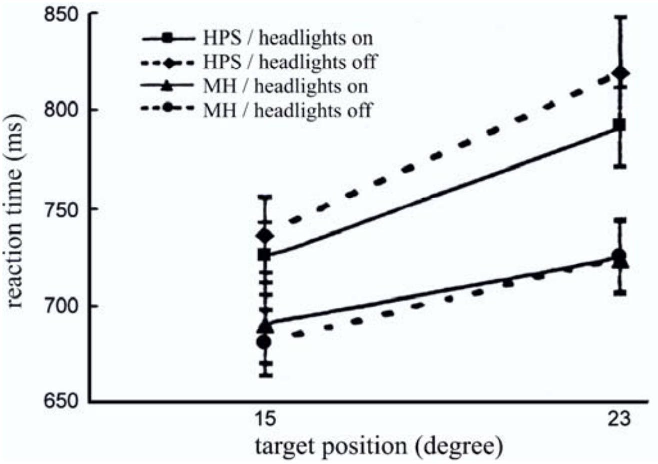


Fig. 4.3 Mean reaction times (and the associated standard errors of the mean) to the onset of a target at 15° and 23° off-axis while driving, with high-pressure sodium (HPS) and metal halide (MH) road lighting, and with halogen headlights turned on and off. The road lighting using the two light sources was adjusted to give similar illuminances and light distributions. The rectangular target subtended $3.97 \cdot 10^{-4}$ steradians for the 15° off-axis position and $3.60 \cdot 10^{-4}$ steradians for 23° off-axis position. Both targets had a luminance contrast against the background of 2.77 (after Akashi and Rea 2001a)

4.1.3 Implications for practice

Given the results discussed above there can be little doubt that light spectrum is a factor to be considered for road lighting, but the implications are rather complex. Specifically, the benefit of choosing a light source that stimulates rod more than cone photoreceptors, depends on the driver's adaptation luminance and the balance between on-axis and off-axis tasks. Provided the adaptation luminance is such that the visual system is operating in the photopic state, there is no effect of light spectrum on off-axis reaction time. If the adaptation luminance is in the high mesopic e.g. about 1 cd/m^2, the effect of light spectrum is slight. It is only when the adaptation luminance is well below 1 cd/m^2 that the choice of light source is likely to make a significant difference to off-axis visual performance. How often this occurs is open to question.

Current road lighting standards recommend average road surface luminances in the range 0.3 to 2 cd/m^2 in Europe (CEN 2002) and 0.3 to 1.2 cd/m^2 in the USA (IESNA 2000). Such luminances are close to the conventional upper end of mesopic vision, and most are above the upper limit of a recent model of a unified system of photometry in which the start of the mesopic is at 0.6 cd/m^2 (Rea et al 2004) This suggests that where there is good quality road lighting there is little benefit to be gained from using light sources that more effectively stimulate the rod photoreceptors, at least with regard to the reaction times to off-axis targets. The same conclusion applies to on-axis detection. Several studies have been made of the effectiveness of different light sources for making largely achromatic objects on the carriageway visible, without any clear conclusions. This suggests that any effects are small (Eastman and McNelis 1963, de Boer 1974, Buck et al 1975). All the measurements were made directly viewing the object i.e. the retinal image fell on the fovea of the retina.

Unfortunately for simplicity, another approach to quantifying the effect of mesopic vision has recently been published (Eloholma et al 2005). The relevant points about this approach are that it is based on performance of a battery of tasks claimed to be relevant to driving, and it appears to show mesopic effects up to 10 cd/m^2. If this approach is more suited to driving then there are likely to be benefits in choosing light sources for road lighting that are more effective in stimulating rod photoreceptors.

But what happens when driving on an unlit road relying on headlights alone? Olson et al (1990) have estimated that the adaptation luminance for a driver using dipped beam headlights on an otherwise unlit road is about 1 cd/m^2. If this were the whole story, then there would seem to be little benefit in considering the use in headlights of light sources that stimulate rod photoreceptors more effectively. Furthermore, then the use in headlights of light sources that stimulate rod photoreceptors more effectively, would be subject to the same conflicting models as road lighting. However, an average luminance masks a wide range, from the hot spot in the beam on the road to the ambient luminance beyond the reach of the headlight beam. Discussion of a single value of adaptation luminance also serves to hide the truth. The fact is the concept of adaptation luminance is a convenient fiction. It was originally developed to describe the effects of luminance on basic visual functions. Its use for this purpose was not unreasonable, as such measurements are usually made on a uniform luminance field. But where the visual field has a wide range of luminances, the adaptation of different parts of the retina will be different, depending on where the eye is fixated. If the driver has one main line of sight, such as might be the case with a driver approaching a tunnel entrance, then the average luminance within about 20° of the fixation point is a reasonable estimate of the adaptation luminance (Adrian 1976). If the observer has many fixation points i.e. the observer is rapidly moving his eyes around, then the average luminance of the whole scene is a good estimate. Measurements of eye movements while driving at night have shown that eye fixations tend to be concentrated around the upper edge of the lit area (Mortimer and Jorgeson 1974; Damasky and Hosemann 1997). Fig. 4.4 shows a contour that defines the area within which fixation occurs 90% of the time when driving on an unlit road using H4 halogen headlights.

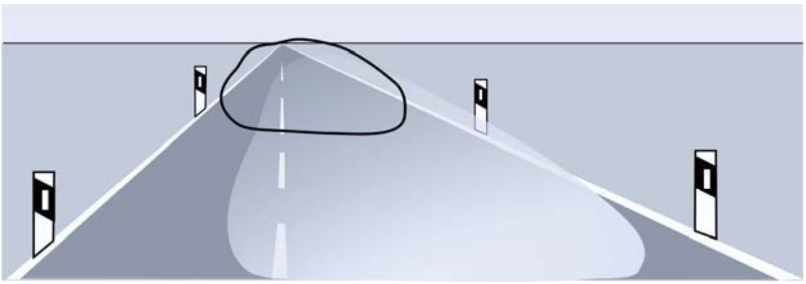


Fig. 4.4 The area within which fixations occur 90% of the time when driving on an unlit road using H4 halogen headlights (after Damasky and Hosemann 1997)

Given that the fixation points while driving on an unlit road do follow the pattern shown in Fig. 4.4, then the lower part of the retina i.e. the part where the road ahead beyond the headlight beam is imaged, could well be operating in the mesopic state, but the upper part will be operating in the photopic state. In this situation, the use of a light source that stimulates the rod photoreceptors more effectively might result in faster detection of objects further up the road. It would be interesting to test this possibility. Comparisons have been made between halogen and xenon headlights and the latter do provide greater visibility distances (Rosenhahn and Hamm 2001). But the difference between the two headlight types involves the amount and distribution of light as well as the spectrum. This being the case it is not possible to quantify the effect of spectrum alone from this data.

One other consideration is the effect of spectrum on discomfort glare. As discussed in the next section, there is evidence that discomfort caused by an off-axis glare source is enhanced by the stimulation of the short wavelength cone photoreceptors. Light sources that stimulate rod photoreceptors more effectively tend to do the same for short wavelength cone photoreceptors. Therefore it can be predicted that a light source that more effectively stimulates rod photoreceptors will produce greater discomfort glare for the same illuminance at the eye. This suggests that there would be some benefit in having different spectra in different parts of the headlight beam. Specifically, a spectrum aimed at stimulating the rod photoreceptors for the whole beam when there is no other vehicle in sight, but a shift to a long wavelength-rich spectrum in the part of the beam likely to be seen by an approaching driver, when one is present.

4.1.4 Mesopic vision – Conclusion

In principle, the existence of mesopic vision and the use of the CIE Standard Photopic Observer in the measurement of light when the visual system is operating in the mesopic state would seem to be a fundamental problem for automotive lighting. As shown above, there is no doubt that light sources that more effectively stimulate the rod photoreceptors enhance the performance of off-axis detection tasks when the visual system is operating in the mesopic state. But at what luminance the mesopic state begins is the subject of controversy. A unified model of photopic, mesopic and scotopic photometry based on reaction times defines mesopic vision starting at 0.6 cd/m^2, while a model of mesopic effects, based on the performance of tasks claimed to be important to driving, defines mesopic vision having an impact up to 10 cd/m^2.

Most road lighting is designed to produce average road surface luminances close to the conventional mesopic / photopic boundary. In this situation, the enhancement of performance is likely to be slight. Where there is no road lighting, so the only light on the road comes from the headlights, there is the possibility of being able to detect objects further down the road, with a light source that more effectively stimulates the rod photoreceptors, Whether this happens, and if it does, how large the effect is, remain to be determined. Until these questions have been answered what to do about mesopic vision as regards automotive lighting will remain an open question.

4.2 Glare

4.2.1 The forms of glare

Glare occurs because while the human visual system can operate over about twelve log units of luminance in total, it can only operate over about three log units simultaneously. Any luminance more than about two log units above the average luminance of the scene will be considered glaringly bright. Exposure to such conditions produces aversion responses e.g. looking away or shielding the eyes. Such behaviour can be taken as an indication that glare is present.

Vos (1999) has classified glare into eight different forms. Of these eight, four occur only rarely. One is flash blindness, a temporary state of complete bleaching of retinal photopigments, caused by the sudden onset of an extremely bright light source e.g. a nuclear explosion. Another is paralysing glare, so named for the phenomenon in which a person suddenly illuminated by a searchlight at night will tend to "freeze" briefly. A third is exposure to light bright enough to cause retinal damage. The last is distracting glare, produced by bright, flashing lights in the peripheral visual field e.g. lights on emergency vehicles at night. These are all special situations remote from conventional automotive lighting, so they will not be discussed further.

The other four forms of glare are more commonly experienced while driving. The first occurs when a large part of the visual field is bright. This is called saturation glare and is painful. The behavioural response is to shield the eyes by wearing low transmittance glasses. Such behaviour is common when driving in very sunny climates.

Saturation glare occurs when a large part of the visual field is at a high luminance for a long time. Another form of glare commonly experienced is adaptation glare. This occurs when the visual system is exposed to a sudden, large increase in luminance of the whole visual field e.g. on leaving a long road tunnel during daytime. The perception of glare is due to the visual system being maladapted. On leaving the tunnel the visual system is adapted to the low light level of the tunnel, but is exposed to the brightness of sunlight. Adaptation glare is temporary, in that the processes of visual adaptation will soon adjust the visual sensitivity to match the new conditions.

The other two forms of glare commonly experienced on roads are disability glare and discomfort glare.

Disability glare

Disability glare, as its name implies, disables the visual system to some extent. This disabling is caused by light scattered in the eye (Vos 1985). The scattered light forms a luminous veil over the retinal image of adjacent parts of the scene, thereby reducing the luminance contrasts of the image of those parts on the retina.

Disability glare can be associated with point sources and large area sources. Disability glare from point sources is experienced most frequently on roads at night, when facing the headlights of an approaching vehicle. Disability glare from an extended source is unusual on the road at night, apart from over-illuminated advertising signs, but it certainly can occur when approaching a road tunnel during daytime. Then, the sky above the tunnel entrance can act as a glare source.

Discomfort glare

Disability glare is well understood. It has an effect on visual capabilities that can be measured with conventional psychophysical procedures and a plausible mechanism, namely light scatter in the eye. On the other hand discomfort glare is not well understood. It is said to be occurring when people complain about visual discomfort in the presence of bright light sources. There is no known cause for discomfort glare, although suggestions have been made ranging from fluctuations in pupil size (Fry and King 1975) to distraction (Lynes 1977).

The separation between disability and discomfort glare should not be taken to mean that disability glare does not cause visual discomfort. Headlights at night can certainly be both visually disabling and visually uncomfortable. In essence, these two forms of glare, disability glare and discomfort glare, are simply two different outcomes of the same stimulus pattern, namely a wide variation of luminance across the visual field.

Spotlight

The origins of glare

The reason why

The human visual system can process information over about 12 log units of luminance, from sunlight to starlight, but not all at once. It continually adjusts itself to the prevailing conditions, aiming at reduced sensitivity and finer discrimination when there is plenty of light available and enhanced sensitivity and coarser discrimination when light is in short supply. When the visual system is adapted to a given luminance, much higher luminances appear as glaringly bright, while much lower luminances are seen as black shadows (Fig. 4.5).

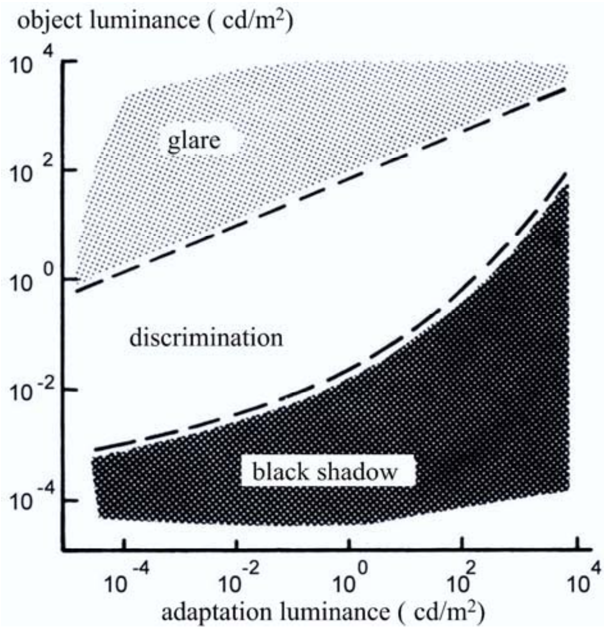


Fig. 4.5 A schematic illustration of the range of object luminances within which discrimination is possible for different adaptation luminances. The boundaries are approximate (after Hopkinson and Collins 1970)

This means that the same luminance can appear dark, comfortable or glaringly bright, depending on the state of adaptation of the visual system. An everyday example of this change in perception is the appearance of a vehicle headlight by day and night. The headlight has the same luminance under both conditions, but as the adaptation luminance decreases as night falls, the headlight becomes very uncomfortable i.e. glare occurs.

The phenomena of glare

Glare is a blanket term for a number of phenomena. The most ubiquitous is a sense of discomfort either associated with a reduction in visibility caused by scattered light in the eye producing reduced retinal image contrast, or with distraction that draws your attention away from where you should be looking. The reduction in visibility is most likely to occur when the glare source is close to the driver's line of sight. Distraction can occur over a wider angular range and is most likely to be associated with small high luminance sources.

Sources of glare

The headlights of an approaching vehicle are the most obvious sources of glare to a driver. They can cause both a reduction in visibility and act as a distraction. While the glare problems posed by headlights are well understood, and have resulted in the light distribution from headlights being carefully controlled, there are a number of other features of a vehicle that can cause glare.

The reflections of the headlights of a following or adjacent vehicle in the interior rear view mirror or the exterior wing mirrors can be a disturbing source of glare, not because they decrease the visibility of the road ahead but because they attract the driver's attention away from the road ahead.

In some countries, vehicles are fitted with high intensity rear lights for use in conditions of poor visibility, such as thick fog. The idea is to increase the luminance of the rear light sufficiently to compensate for the increased absorption and scattering of light by the atmosphere. If such rear lights are only used in conditions of poor visibility, they are not a source of glare, but unfortunately, the choice of normal or high intensity rear lights is under the manual control of the driver. Some drivers switch to high intensity rear lights at the first hint of rain. The result is glare for the following driver, causing him discomfort, and limiting his visibility of the vehicle ahead. It may also make the onset of brake lights more difficult to recognise. In dense traffic, momentary glimpses of high intensity rear lights in the distance may be interpreted as brakes being applied, resulting in unnecessarily jerky driving.

Above a certain luminance the instrument display can also be a source of glare. The effect is primarily one of distraction rather than reduced visibility of the road ahead.

Finally, there is the possibility of the fascia around the windscreen becoming an extended glare source. If the materials chosen for the car interior are of high reflectance, inter-reflected light from following vehicles, or from interior lighting, can raise the luminance of the fascia sufficiently for it to become a source of disability glare. The result will be a reduction in the visibility of the road ahead. It is interesting to contemplate that glare produced in this way occurs when the light sources producing the glare are not visible to the driver.

Possible solutions

Possible solutions to the problem of glare from headlights are discussed elsewhere.

Interior rear view mirrors that automatically change their reflection properties when a high illuminance is detected falling on the mirror are already fitted to some luxury vehicles. Extending such technology to exterior mirrors and other vehicles is a matter of economics.

Instrument displays are rarely a glare source today as most vehicles allow drivers to adjust the luminance of the display over a wide enough range to avoid discomfort.

As for the choice of materials for the car interior, this is subject to many considerations, reflectance being just one of them. Nonetheless, high reflection materials should be used with caution, particularly for the fascia.

4.2.2 The quantification of glare

Formulae exist for the quantification of both forms of glare.

Disability glare

The amount of disability glare can be measured by comparing the visibility of an object seen in the presence of the glare source, with the visibility of the same object seen through a uniform luminous veil. When the visibilities are the same, the luminance of the veil is a measure of the amount of disability glare produced by the glare source, and is called the equivalent veiling luminance. Numerous studies have led to several different empirical methods for predicting the equivalent veiling luminance (Holladay 1926; Stiles 1930; Stiles and Crawford 1937). Based on this work, an equation was developed to predict the equivalent veiling luminance from directly measurable variables. It is

$$L_v = 10 \cdot \sum E_n \cdot \Theta_n^{-2}$$

…where L_v = equivalent veiling luminance (cd/m²)
E_n = illuminance at the eye from the n-th glare source (lx)
Θ_n = angle between the line of sight and the n-th glare source (degrees)

The disability glare formulae can be applied directly to point sources but for large area sources, the area has to be broken into small elements and the overall effect integrated (Adrian 1976).

The effect of the equivalent veiling luminance on the luminance contrast of an object can be estimated by adding it to the luminance of both the object and the immediate background. The result is an inevitable reduction in the luminance contrast of the object, as shown by the increase in the denominator of the following equation.

$$C = \frac{((L_{\max} + L_v) - (L_{\min} + L_v))}{((L_{\max} + L_v) + (L_{\min} + L_v))}$$

$$C = \frac{(L_{\max} - L_{\min})}{(L_{\max} + L_{\min} + 2 \cdot L_v)}$$

...where C = luminance contrast
L_{max} = maximum luminance (cd/m²)
L_{min} = minimum luminance (cd/m²)
L_v = equivalent veiling luminance (cd/m²)

It is important to note that the formula for equivalent veiling luminance given above applies to glare sources positioned between 1° and 30° from the line of sight, and only for young test persons. Hartmann and Moser (1968) have shown that for angles less the 100 min arc. from the line of sight, the loss of visibility associated with disability glare is much greater than would be predicted from the disability glare formula. This is probably because of neural interactions occurring in the retina in addition to light scatter in the eye. As for the effect of age, the elderly have much more turbid optic media than the young, resulting in much greater absorption and scattering of light as it passes through the eye. Consequently, the CIE has developed a modified disability glare formula suitable for use in the angular range 0.1° to 30°, and for either young or old people (CIE 2002). This equation takes the form:

$$L_v = \sum \left(\frac{10 \cdot E_n}{\Theta_n^3} + \left(1 + \left(\frac{A}{62.5}\right)^4\right) \cdot 5 \cdot \frac{E}{\Theta_n^2} \right)$$

…where L_v *= equivalent veiling luminance (cd/m²)*
A = age (years)
E_n *= illuminance at the eye from the n-th glare source (lx)*
Θ*= angle of the n-th glare source from the line of sight (degrees)*

In both the simple and the elaborated formulae for equivalent veiling luminance, the only photometric quantity involved is the illuminance received at the eye. This implies that for the same illuminance at the eye, the spectrum of the light received is unimportant, as is the size of the light source and hence the luminance. There is some support for these implications (Flannagan 1999).

Discomfort glare

Schmidt-Clausen and Bindels (1974) have produced an equation relating the illuminance at the eye to the level of discomfort produced by headlights, expressed on the de Boer scale. The equation is

$$W = 5.0 - 2\log(E / 0.003(1 + \sqrt{(L/0.04) \cdot \phi^{0.46}})$$

…where W = Discomfort glare rating on the de Boer scale
E = Illuminance at the eye (lx)
L = Adaptation luminance (cd/m²)
ϕ *= Angle between line of sight and glare source (min. arc)*

The de Boer Scale is a nine point glare scale with five anchor points labelled 1 = unbearable, 3 = disturbing, 5 = just admissible, 7 = satisfactory, 9 = unnoticeable. Conditions producing ratings of 4 or less are usually considered uncomfortable.

Again, the only photometric quantity in the equation related to the glare source is the illuminance received at the eye. However, for discomfort there is evidence that other factors have small effects. While the perception of discomfort from headlights is dominated by the illuminance at the eye (Sivak et al 1990; Alferdinck 1996), light spectrum (Flannagan et al 1989), headlight size (Alferdinck 1991) and light dose (Van Derlofske et al 2005) all have small effects on discomfort. Specifically, for the same illuminance at the eye, light spectra with more energy at the short wavelength end of the visible spectrum, smaller headlight sizes and longer exposure times will all tend to cause more discomfort.

4.2.3 Performance in the presence of glare

The most obvious and best understood consequence of exposure to glare is a reduction in contrast of the scene around the glare source. This should lead to a reduction in the ability to detect targets that are close to threshold in the absence of glare. One way to examine this effect is to measure the detection distance for obstacles as two vehicles approach and pass each other. Mortimer and Becker (1973), using both computer simulation and field measurements, have shown that the visibility distance for targets of reflectances 0.54 and 0.12 diminish as opposing cars close, and then start to increase rapidly (Fig. 4.6). The separation at which the visibility distance is a minimum depends on the relative luminous intensity distribution of the headlights, the relative positions of the two vehicles, the obstacles to be seen, and the physical characteristics of the obstacle.

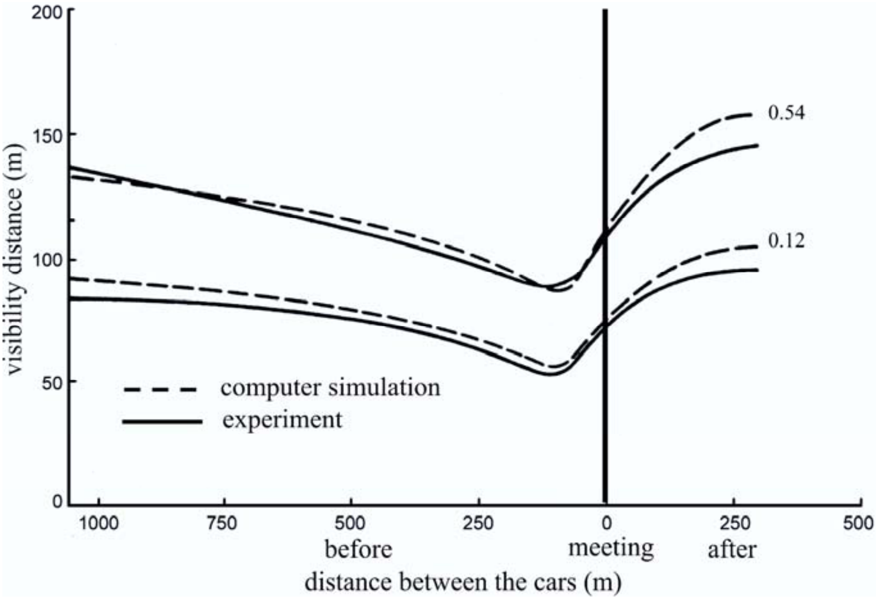


Fig. 4.6 Visibility distance for targets of reflectance 0.54 and 0.12, plotted against the distance between two vehicles approaching each other, with headlights of equal luminous intensity (after Mortimer and Becker, 1973)

Helmers and Rumar (1975) measured visibility distances for flat, dark-grey 1.0 m by 0.4 m rectangles with a reflectance of 0.045. Observers were driven towards a parked car with its headlights on and asked to indicate when they saw the obstacles. It was found that for the small dark-grey obstacle, a headlight system with the maximum high beam luminous intensity gives a visibility distance of about 220 m, when no opposing vehicle is present. This is the same as the stopping distance for a vehicle moving at 110 km/h, which is about 220 m on wet roads (AASHTO 1990). However, when two opposing vehicles have equal luminous intensity headlights, the visibility distance is reduced to about 60 - 80 m, which is much less than the stopping distance. When the opposing vehicle has a luminous intensity about three times more than the observer's vehicle, the visibility distance is reduced to about 40 - 60 m. It is clear that driving at high speeds against opposing traffic at night approaches an act of faith…

Spotlight

Luminance as criterion to evaluate disability and discomfort glare

Designing a vehicle headlamp is always a trade-off between high visible range for the driver and a minimum of glare for the oncoming traffic. The first is accomplished by bringing a lot of light on the road and the latter by minimising the light that reaches the driver of the oncoming car. Both a maximum of visual range and a minimum of glare are crucial for safety at night.

This design trade-off has always been a focus when introducing new headlamp technologies to the market. Projection systems were established at the same time as the introduction of the first gas discharge lamps with a much higher luminous flux than common halogen lamps. Thus the common reflector was no longer used to distribute light. The projection systems use a lens, the size of which defines the light emitting area of the headlamp. The projection lens is usually much smaller than the reflector size, but equipped with a gas discharge lamp, the emitted luminous flux is approximately 2.5 times higher compared to a halogen lamp. This leads to higher luminances of the light source, irrespective of the level of illuminance. This effect may be intensified by future headlamps.

The limitation of glare for automotive headlamps is today solely based on a maximum value of illuminance at the point B50L on the ECE testing wall. Further parameters and criteria such as the spectrum of the glare source and the size of the light emitting area of the headlamps are not considered as critical to minimise glare. The regulations limit the illuminance caused by one headlamp at B50L to 0.4 lx for halogen and to 0.5 lx for gas discharge systems. Despite these limitations, gas discharge lamps are often regarded as more glaring than halogen lamps. Given the facts that glare sensitivity is influenced by many more criteria than the illuminance of the glare source, and that luminance is the photometric quantity that describes human brightness perception, one might ask whether luminance of the glare source is also a significant influencing parameter that should be considered for regulations.

In comparison to the influence of illuminance, which has been examined in various studies, luminance with respect to the size of the glare source as an influencing parameter on glare was not investigated very extensively. Sivak (1988) and Alferdinck (1991) examined the influence of the size of the glare source, reporting a minor but significant effect on discomfort glare.

The following figures show the results of a study that examined the effect of luminance with respect to size on discomfort as well as disability glare, at constant levels of illuminance. Disability glare is quantified by measuring the visual impairment caused by the glare source e.g. the increase of threshold contrast, the luminance ratio at which an object is just noticeable. The average threshold contrast versus the luminance and the size of the glare source is given in Fig. 4.7 and Fig. 4.8 for different illuminance levels.

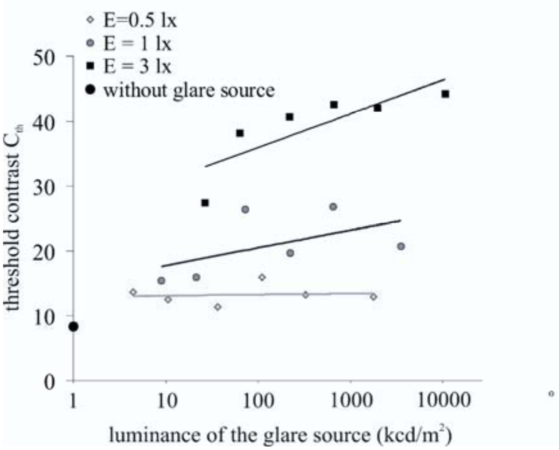


Fig. 4.7 Disability glare described by the increase of the contrast threshold $C_{th} = L_{obj}/L_{backgr}$ vs. the luminance of the glare source in kcd/m^2, for three glare illuminances, compared to the threshold contrast measured without glare

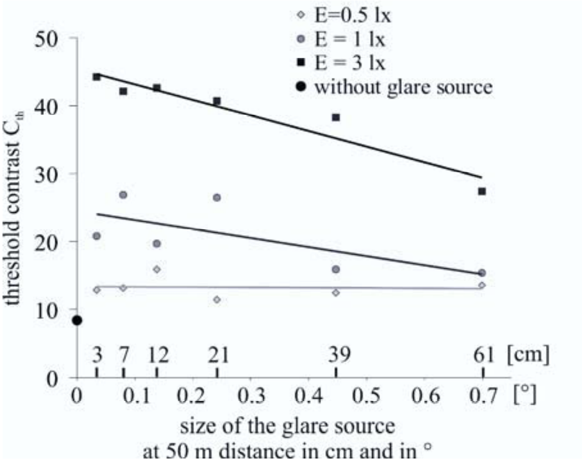


Fig. 4.8 Disability glare described by the increase of the contrast threshold $C_{th} = L_{obj}/L_{backgr}$ vs. the diameter of the glare source in cm and degrees for three glare illuminances, compared to the threshold contrast measured without glare

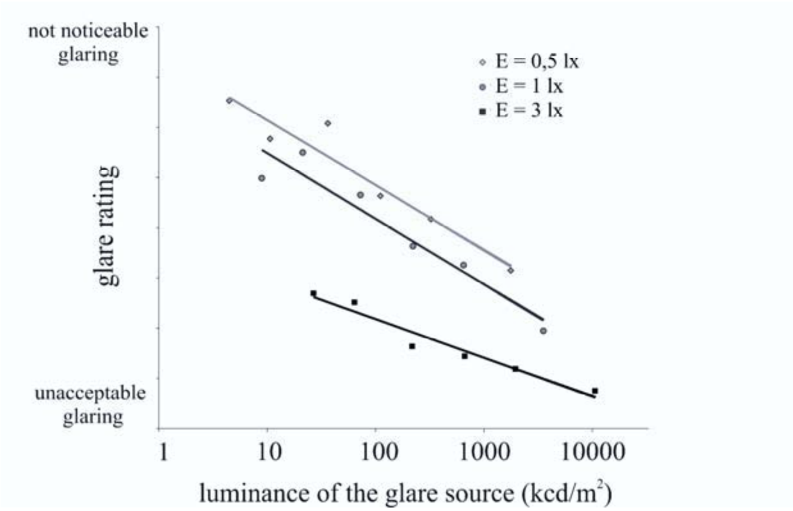


Fig. 4.9 discomfort glare rating vs. the luminance of the glare source in kcd/m^2 for three glare illuminance levels

For 0.5 lx, the upper limit for gas discharge headlamps set by the ECE, no effect was found. For higher levels of illuminance which also occur in traffic e.g. from incorrectly adjusted headlamps, and on crests, an influence of luminance on disability glare can be seen. Even though the illuminance has the strongest impact on disability glare, a limitation of the size or luminance can reduce visual impairments due to oncoming traffic.

Discomfort glare describes the level of disturbance by the glare source and is measured by rating the glare impression. The subjective evaluation for several sized glare sources is shown in Fig. 4.9 and Fig. 4.10 for three illuminance levels.

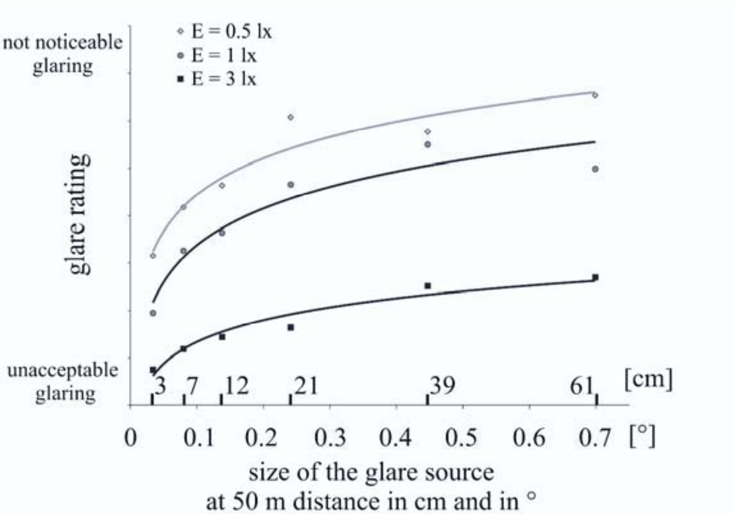


Fig. 4.10 discomfort glare rating vs. the diameter of the glare source in cm and degrees for three glare illuminance levels

The results illustrate that the discomfort glare perception is not solely based on the illuminance level, but also on luminance that directly correlates with the size of the glare source for constant levels of illuminance. This influence is relevant in particular for the three smallest glare sources that are in the range of today's headlamps. In comparison to the results for disability glare, these effects are also found for low levels of illuminance.

In conclusion we can say that although the level of illuminance is still the most decisive parameter on both disability and discomfort glare, it is advisable not to restrict the prevention of glare to this single parameter. Even if all headlamps fulfil the legal requirements, some are perceived as more glaring than others. In general it can be said that there is a correlation between glare for oncoming drivers and the luminance with respect to the size of the light emitting area of the glare source. It has however yet to be shown in which way discomfort and disability glare influence safety and comfort in traffic.

Spotlight

Don’t kill the jogger

The value of light

The presence of light reduces pedestrian fatalities. Fig. 4.11a shows the total number of fatal pedestrian accidents in 46 States of the USA occurring during the hour around dawn in the nine weeks before and after the spring daylight saving change (Sullivan and Flannagan 1999). It can be seen that in the weeks before the change, there is a steady decrease in the number of fatal accidents. But at the daylight saving change, there is a rapid return to a high level of accidents, a level that then reduces with the increasing day length. Fig. 4.11b shows analogous data for the hour around dusk. For the evening, the effect of the daylight saving change is to change the driving conditions for the same driving population from night to day. The dramatic decrease in the number of fatal pedestrian accidents with this transition is obvious. It should be noted that tiredness resulting from the daylight saving change is not a plausible explanation for these results. The human circadian system can shift its phase by about an hour a day, so adjustment to the daylight saving change should be complete within a day.

The data presented in Fig. 4.11 show the value of light to pedestrian safety. But this should not be taken to mean that light is of value for all types of accidents. Sullivan and Flannagan (1999) carried out a similar analysis for fatal accidents involving a single vehicle leaving the road on curved, rural, high-speed roads. For this type of fatal accident the change in lighting conditions produced by daylight savings time showed very little change in the number of fatal accidents. The difference in the results for the two accident types reflects the underlying causes of the accidents. Pedestrian fatalities are commonly caused by the failure of the driver to see the pedestrian. Single vehicles leaving the road are much more likely to occur because of either fatigue or intoxication.

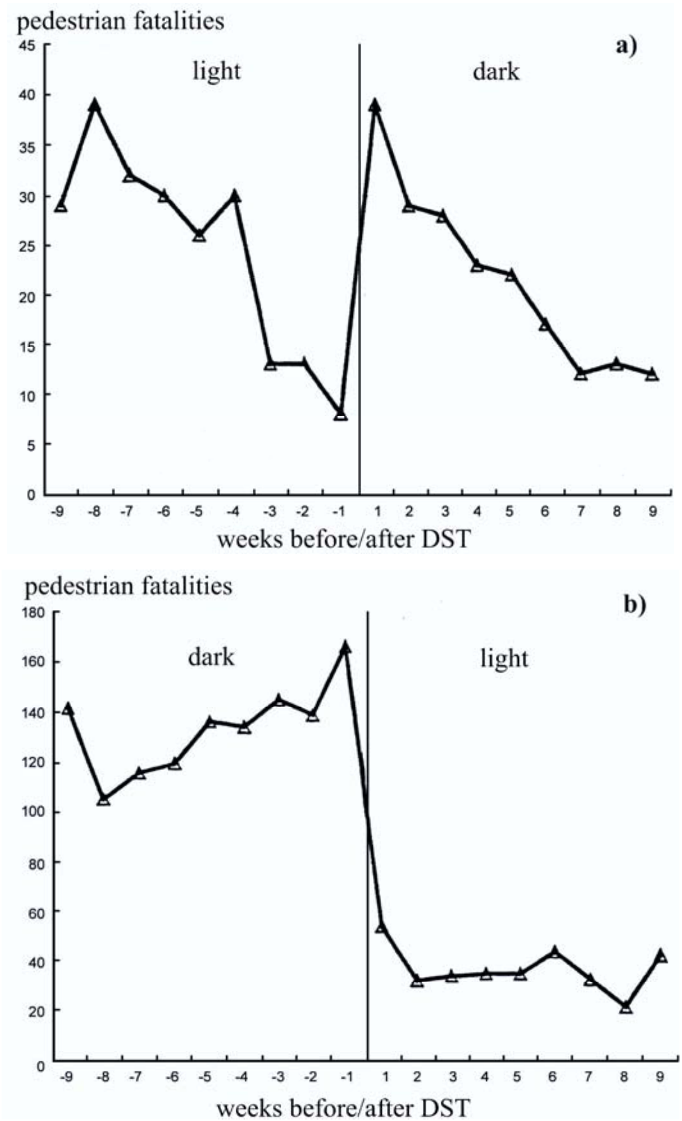


Fig. 4.11 Average number of pedestrian fatalities in forty-six states of the United States, over the years 1987 to 1997, during twilight, for the nine weeks before and after the Spring daylight saving time change (upper graph) for morning, (lower graph) for evening (after Sullivan and Flannagan 1999)

Why is current lighting practice inadequate?

Given that the presence of light enhances the safety of pedestrians, it is appropriate to ask why the existing provision of vehicle lighting, and in some places, road lighting, is inadequate. To answer this question, it is necessary to consider why pedestrians are not seen. The first and most obvious reason is the tendency for pedestrians to wear dark clothing. At night, unless walking on snow, dark clothing inevitably means low contrast for the pedestrian against the immediate background. Contrast is the primary factor in determining visibility. The second is driver expectations. We tend to see what we expect, so that if we do not expect pedestrians to be present, we are less likely to see them. Further, if we do not expect pedestrians to be present we are unlikely to fixate their location, in which case the pedestrian has to be detected off-axis where detection is less likely. All the above apply when both vehicle lighting and road lighting are present. When the driver is using vehicle lighting alone, there is another factor to be considered, namely the limited range of visibility provided by headlights, particularly when dipped. As a consequence of this limited range, the time available for the driver to respond to the presence of a pedestrian, even if he has been detected, is very short.

Reducing pedestrian fatalities

What can be done to alleviate this situation? There is little that can be done about drivers' expectations, because these depend on experience and knowledge of the locality. However, the pedestrian can do much to enhance his visibility by wearing light clothing and/or markings that provide high luminances e.g. retroreflectors. High reflectance clothing is better than markings, because although both will aid detection, clothing will make it easier for the driver to identify what has been detected as a pedestrian. As for lighting, both vehicle lighting and road lighting could be configured to provide more light and hence greater emphasis on the side of the road. This would increase the safety of the pedestrian at the side of the road, but it would not really benefit the pedestrian crossing the road.

Spotlight

Reducing the stress of driving

Two extreme situations

Driving can be stressful. Stress can occur at the two extremes of information extraction. One extreme occurs when there is no information where there should be. An example of this is driving in thick fog. In this situation, the whole world is uniform in luminance, yet we know the road has edges and there may be other people and vehicles on it. A common behaviour pattern when driving in thick fog is to get behind a vehicle ahead and then stay close. This reduces the stress of driving because it limits the amount of information we need to extract. All we need to do is follow the vehicle ahead, leaving the driver of that vehicle to sort out the unknown. The risk in this behaviour is that you are relying on the driver ahead not to lead you into danger.

At the other extreme of information extraction is information overload. An example of this is driving during the rush hour at night in a strange city in the pouring rain. Information arrives from all directions in overwhelming quantities, but the information you want may be hidden. There is little that can be done about the weather, but if you feel stressed about the prospect of driving in a strange city, try to arrive during daylight, and not during the rush hour.

The role of vehicle lighting

In between these two extremes lies a condition of minimum stress, where the information being sought is readily available and does not require a rapid response. This most commonly occurs during the day, but vehicle lighting has a role to play in achieving this nirvana after dark. Its role is to make it easier to extract the necessary information and to relax the necessary speed of response. Driving on an unlit road using high beam headlights is less stressful than driving using dipped headlights, because visibility is better over a larger area and the driver can see further down the road. In this situation, the driver has more time to detect, identify and respond to whatever lies ahead. Road lighting can fulfil a similar purpose.

The limitations of light in snow and fog

It is important to note that making more light available may not be beneficial for driving in dense fog and snow. In fog, the additional light output produced by the high beam headlights produces additional scattered light, which tends to reduce the contrast of whatever is present, thereby reducing its visibility. In snow, additional light reflected back from the snowflakes increases their visibility. The problem with this is that the snowflakes are a distraction from the information needed. For driving in both fog and snow, dipped highlights will usually be less stressful than high beam headlights. For driving in fog, low mounted fog lights with a wide, flat beam are even better, because fog is usually thinner close to the ground, so that less light is scattered per unit path length. For driving in snow, any additional lighting is best mounted as far away from the line of sight of the driver as possible, because then the increase in the luminance of the snowflakes, as seen by the driver, is minimised.

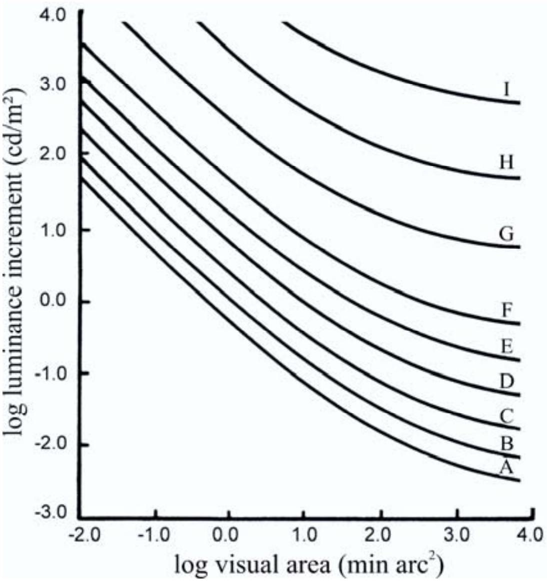


Fig. 4.12 Relationships between log luminance increment and log visual area at different background luminances, for small targets to be just visible. Each curve is for one background luminance as follows: A = 0.01 cd/m^2, B = 0.1 cd/m^2, C = 0.32 cd/m^2, D = 1.0 cd/m^2, E = 3.2 cd/m^2, F = 10 cd/m^2, G= 100 cd/m^2, H = 1000 cd/m^2, I = 10,000 cd/m^2 (after Hills 1976)

The targets used in the studies for contrast threshold do not emit light, but are seen by reflected light. Signal lights on vehicles are self-luminous. It is now necessary to consider to what extent exposure to glare from headlights might reduce the visibility of signal lights. The signal lights closest to the glare source will be those on the approaching vehicle next to the headlights. These may be sidelights, in which case their visibility is of little consequence, since the presence of the headlights is enough to mark the approaching vehicle. But they may be turn indicators, in which case not being able to see the signal light would matter. Regulations specify different luminous intensities for a turn indicator depending on the separation from the headlight.

Another situation of interest is the visibility of signal lights far enough ahead that the signal lights are not illuminated by the headlights of the driver's vehicle. Hills (1976) has produced a predictive model of the relationship between luminance increment and area for small targets, such as rear lights and pedestrians, to be just visible for a wide range of background luminances (Fig. 4.12). The ordinate in Fig. 4.12 is the logarithm of the increment of the object luminance necessary for it to be just visible against the background luminance. Different values of background luminance enable the effects of different lighting conditions to be estimated, from starlight, via road lighting, to daylight. The effect of disability glare can be taken into account by adding the equivalent veiling luminance to the background luminance.

4.2.4 Recovery from glare

The discomfort experienced when exposed to headlights is replaced by a feeling of relief almost immediately after the other vehicle passes. Likewise, the light scattered in the eye disappears with the glare source. But that does not mean vision is immediately restored to the state existing before exposure to glare. The additional light that has reached the retina of the driver from the approaching headlights will have had an effect on the state of adaptation of the photoreceptors. Therefore immediately after the other vehicle passes, the driver's vision will be maladapted. The process of adjusting adaptation is called recovery from glare.

Van Derlofske et al (2005) examined what factors determined the time taken to recover from glare. The subject was exposed to four different glare stimuli (Fig. 4.13). Two have the same maximum illuminance at the eye, but produce different light doses, this being the product of illuminance and time of exposure. The other two have an equal light dose but different maximum illuminances at the eye. Immediately after exposure, the subject was presented with a square target, the contrast of which was a fixed ratio of the individual's threshold contrast. The subject's task was to indicate when the target could first be seen. Fig. 4.14 shows the recovery times for different contrast ratios above threshold and for the different glare exposure profiles. From Fig. 4.14 it is evident that recovery times are shorter for the higher contrast target. Furthermore the recovery time is determined by the light dose and not the maximum illuminance. It is interesting to note that in the same experiment it was shown that ratings of discomfort on the de Boer scale were more closely related to the maximum illuminance at the eye than the light dose.

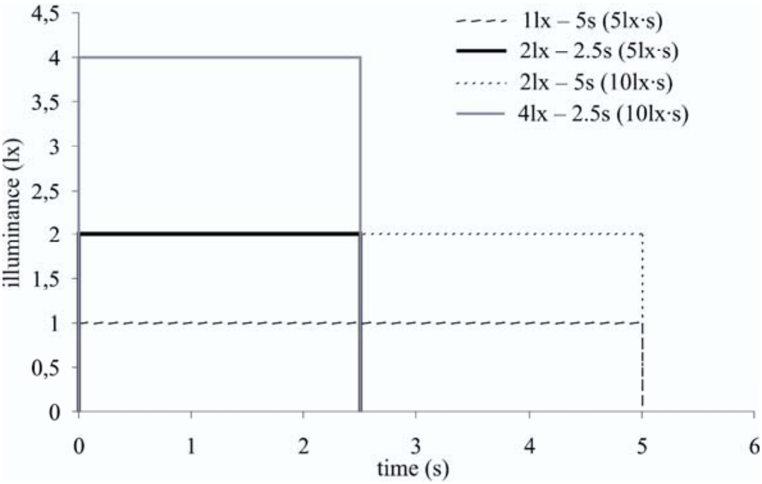


Fig. 4.13 The four glare stimuli used by Van Derlofske et al (2005) showing the maximum illuminance at the eye and the duration of exposure. The effect of these stimuli is to produce three different maximum illuminances and two different light doses

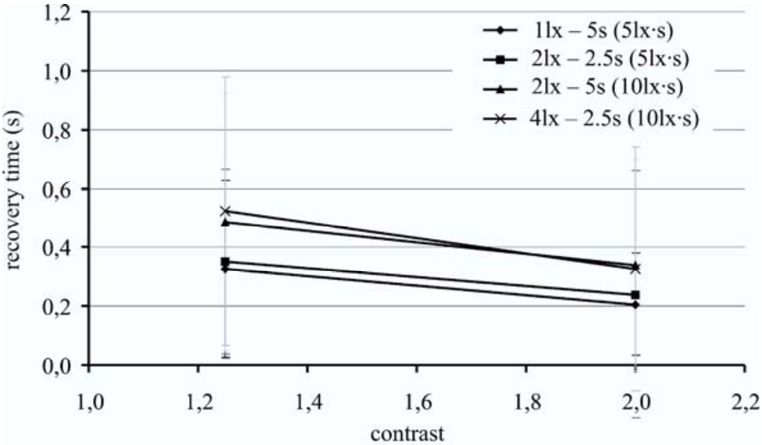


Fig. 4.14 Mean detection times for targets after exposure to the four glare illuminance profiles shown in Fig. 4.13 plotted against target contrast. Target contrast is expressed as ratio of the threshold contrast without glare (Van Derlofske et al 2005)

4.2.5 Behaviour in glare

Different illuminances received at the eye can be associated with different behaviours. The range of illuminance received at the eye during normal driving is from 0 to 10 lx (Alferdinck and Varkevisser 1991). Within this range, illuminances of the order of 1 to 3lx are sufficient to cause drivers to request dipping from the approaching vehicle (Rumar 2000). Illuminances of 3lx and more are likely to be considered very uncomfortable (Bullough et al 2002).

Given that the approaching driver does not respond to a request for dipping, how does the requesting driver respond? Theeuwes and Alferdinck (1996) conducted a test where people drove over urban, residential and rural roads at night, with a glare source simulating the headlights of an approaching vehicle mounted on the bonnet of the car. They found that people drove more slowly when the glare source was on, particularly on dark winding roads where lane-keeping was a problem. Older subjects showed the largest speed reduction. The presence of glare also caused the drivers, particularly older drivers, to miss many roadside targets.

Spotlight

"Headlights aren't nearly as good as they used to be…"

Vision changes with age

As the visual system ages, a number of changes in its structure and capabilities occur. With increasing years the ability to focus close up is diminished, the amount of light reaching the retina is reduced, more of the light reaching the retina is scattered, the spectrum of the light reaching the retina is changed and more stray light is generated inside the eye. The consequences of these age-related optical changes for the capabilities of the visual system are many and varied. At the threshold level, old age is characterised by reduced absolute sensitivity to light, reduced visual field size, reduced visual acuity, reduced contrast sensitivity, reduced colour discrimination and greater sensitivity to glare. On the road, the elderly have difficulty seeing far at night, moving from bright to dark conditions suddenly as on entering a tunnel during the day, detecting low contrast pedestrians at night and recovering from glare exposure. On top of all this are the changes in their cognitive capacity that occur simultaneously. These make understanding a dynamic situation more difficult and the necessary responses slower.

Behavioural changes

As a consequence of these changes, the elderly tend to modify their behaviour. The most extreme behaviour modification is to give up driving at night entirely. Less extreme but also common behaviours are to restrict the routes taken at night to those that are familiar and to drive more slowly. Also frequently found are drivers who adjust their speed according to the circumstances. So next time you are behind a vehicle travelling unusually slowly at night, or one that slows down markedly every time another vehicle approaches, have a little patience and remember that if you are lucky, you will be that driver one day.

Helping the elderly driver

The elderly driver is faced with two major problems: the need to make decisions rapidly and a reduced ability to collect the information on which to base those decisions. Any lighting that gives the elderly driver more time in which to collect the necessary information and to act on it will be beneficial.

Probably the most useful contribution in this respect is made by road lighting. Good quality road lighting i.e. road lighting providing a high road surface luminance without glare, will allow the elderly driver to explore the road a considerable distance ahead. It will also provide guidance about the direction of the road. Further, by increasing the background luminance, good road lighting will also reduce the impact of glare produced by headlights.

As for vehicle lighting, the major contribution it can make to the abilities of the elderly driver is in the limitation of glare. This requires attention to installation and to use. There is an inevitable conflict between the driver behind a set of headlights and the driver facing them. The driver behind the headlights wants them to be a bright as possible while the driver facing them wants them to be as dim as possible. So far, the compromise adopted to resolve this conflict is the two state, main and dipped beam headlight, although the future may offer much more effective opportunities. At the moment, the essential actions you can take to limit glare are to keep your vehicle’s headlights clean and to switch to dipped headlights whenever another vehicle approaches, well before that vehicle is close. It is also worth remembering that glare can also be caused by headlights seen in mirrors, so be sure to switch to dipped headlights as you approach a vehicle from the rear.

4.2.6 Glare in practice

So far this discussion of glare has been concerned with the phenomenon rather than the reality. In practice, headlight systems are designed to meet different specifications in different parts of the world. Further, there is a large difference between the luminous intensity distribution of a new headlight and a headlight on a vehicle that has been on the road for some time. Headlights on a vehicle on the road may produce different luminous intensities in important directions, because the vehicle may not be level, or the headlight is incorrectly aimed or dirty. Yerrel (1971) reported a set of roadside measurements of headlight luminous intensities in Europe and found a very large range of luminous intensities for the same direction. Alferdinck and Padmos (1988) found similar results from roadside measurements in the Netherlands. They also examined the importance of aiming, dirt and lamp age on the luminous intensity in a series of laboratory measurements.

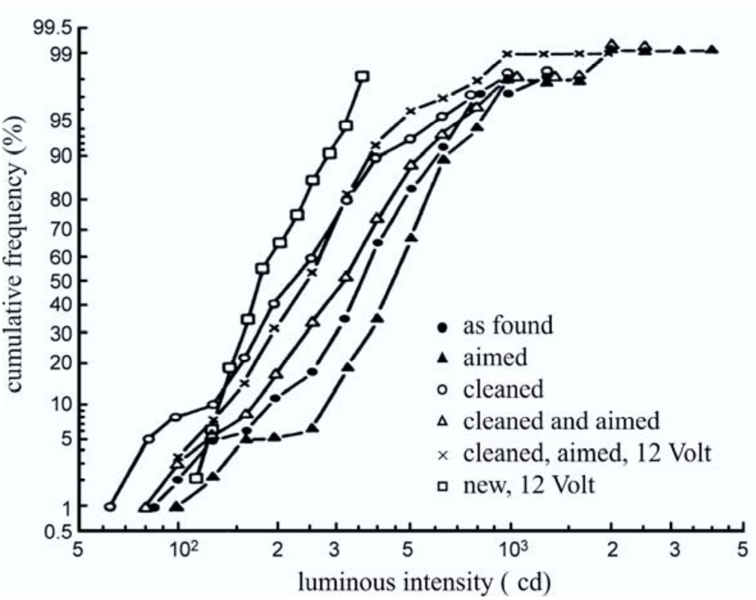


Fig. 4.15 Cumulative frequency distributions of luminous intensities in a direction important for glare to oncoming drivers, for headlights on fifty cars as found; aimed; cleaned; cleaned and aimed; cleaned, aimed and operated at 12 V; and for new headlights (after Alferdinck and Padmos 1988)

Fig. 4.15 shows the cumulative frequency distributions of luminous intensity in a direction important for glare to an oncoming driver, for fifty cars taken from a parking lot. From Fig. 4.15 can be seen that the headlights, as found, tend to produce more glare than new headlights. Adjusting headlights which were aimed too low makes things slightly worse. But cleaning headlights reduces glare caused by luminous intensity and again brings it close to that of new headlights. The ranges of luminous intensities shown in Fig. 4.15 suggest that fine differences between the recommended headlight luminous intensity distributions used in America and in Europe are trivial compared to the differences that occur in practice, due to aiming, lamp age and dirt. This in turn supports the installation of automatic levelling and cleaning systems for headlights on vehicles.

4.2.7 Xenon and halogen headlights

The most dramatic change in headlights over the last decade has been the widespread adoption of the high intensity discharge (HID, xenon) headlight. Xenon headlights differ from conventional halogen headlights in three respects; the size of the light source, the luminous intensity distribution from the headlight and the spectral power distribution of the light emitted.

The arc tube of the xenon light source is smaller than the filament of halogen light sources, with the result that headlights using xenon light sources can be smaller. This is of little consequence for glare, because headlights usually subtend such a small solid angle from the normal viewing distance, that headlight area has only a small effect on discomfort.

As for the luminous intensity distribution of xenon headlights, the recommended minimum and maximum luminous intensities used in different parts of the world, apply regardless of the light source used; so xenon headlights are designed to meet these requirements. However, the xenon light source has a much higher luminous efficacy than halogen light sources. Thus xenon headlights typically have a higher maximum luminous intensity than tungsten-halogen headlights. They also send more light to the sides of the vehicle in areas that are not controlled by the current regulations. These differences in the amount and distribution of light from xenon headlights, together with the variability introduced by aiming, dirt, and the different geometries that can occur between two approaching vehicles, are probably enough to explain the widespread anecdotal complaints of disability and discomfort glare from drivers meeting vehicles equipped with xenon headlights. It also explains why people driving vehicles equipped with xenon headlights like them. Fig. 4.16 shows contours for the detection of a 40 cm square target of reflectance 0.1, by drivers using either dimmed xenon headlights or dimmed halogen headlights (Rosenhahn and Hamm 2001). Clearly, the xenon headlights conforming to the same regulations, allow objects to be detected at greater distances and over a wider range of angles than tungsten halogen headlights. It is also worth noting that a driver meeting a car equipped with xenon headlights is likely to be exposed to higher illuminances for longer than if the car was using tungsten halogen headlights. Consequently, the time for recovery from glare should be longer for the xenon headlight.

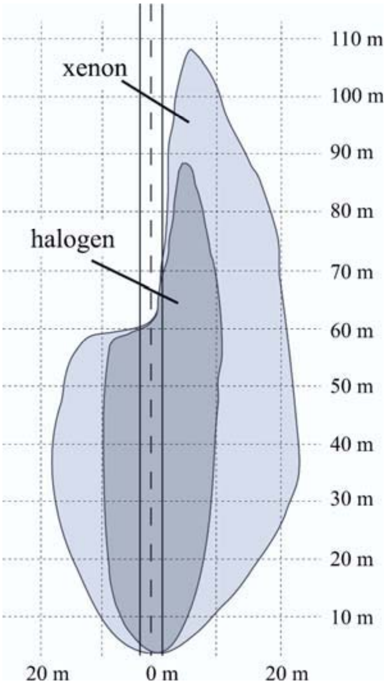


Fig. 4.16 Contours for the distance at which a target 40 cm square, with a reflectance of 0.1, is detected by drivers for either dipped xenon headlights or dipped halogen headlights (after Rosenhahn and Hamm 2001)

The spectral power distribution of the xenon headlight is very different from that of the halogen headlight having much more energy at the short wavelength end of the visible spectrum. This alone will tend to lead to greater discomfort for the same illuminance at the eye (Bullough et al

2003). Fig. 4.17 shows ratings of discomfort on the de Boer rating scale for tungsten halogen and xenon headlights (Fu 2001). It is clear that the illuminance at the eye is the major factor in producing discomfort, but there is no doubt that the spectrum has an effect as well.

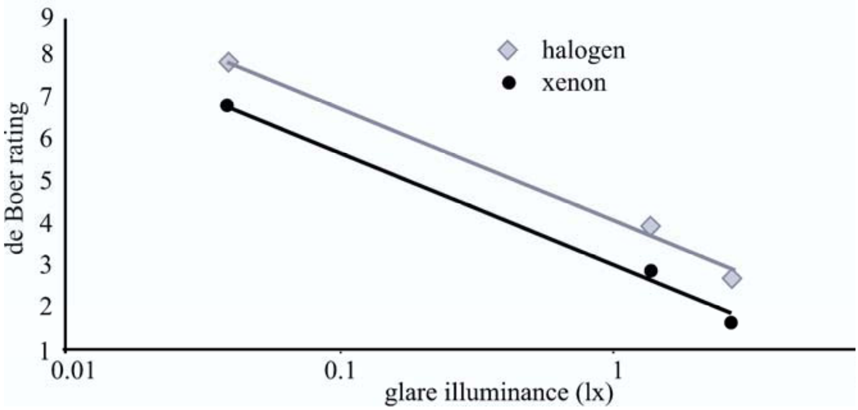


Fig. 4.17 Mean de Boer glare ratings for exposure to halogen and xenon headlights producing the same illuminances at the eye (after Fu 2001)

To evaluate the effect of any specific headlight spectrum on discomfort glare, Dee (2003) has proposed a spectral sensitivity curve as follows:

$$V_{dg}(\lambda) = V_{10}(\lambda) + (0.19 \cdot SWC(\lambda))$$

…where $V_{dg}(\lambda)$ = Discomfort glare spectral sensitivity
$V_{10}(\lambda)$ = Photopic spectral sensitivity for a 10 degree field
SWC $(\lambda))$ = Short wavelength cone spectral sensitivity

The discomfort glare spectral sensitivity normalised to unity is shown in Fig. 4.18. This discomfort glare spectral sensitivity has been shown to rectify discomfort glare ratings for conditions simulating exposure to headlights from both white light and monochromatic glare sources (Watkinson 2005).

Given the tendency for expensive options first introduced in up-market vehicles to gradually spread into cheaper vehicles, it seems likely that xenon headlights will soon become much more widely used, replacing halogen headlights, just as they replaced tungsten headlights. This is also likely because the higher luminous intensities available with xenon headlights and the smaller possible headlight sizes place fewer constraints on automobile design. The problems of disability and discomfort glare can be solved by regulating the maximum luminous intensity allowed in all directions relevant for glare. This could be achieved by more precise optical design, and by greater attention to the aiming and cleanliness of headlights already installed in vehicles. Already some countries require that a vehicle equipped with xenon headlights be fitted with a self-levelling suspension, while others require the installation of headlamp cleaning systems.

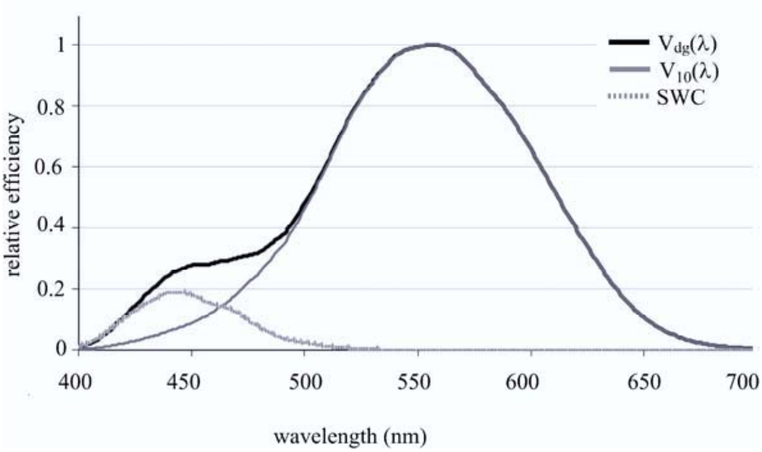


Fig. 4.18 Proposed discomfort glare spectral sensitivity normalised to unity (after Watkinson 2005)

4.2.8 Conclusion

By now it should be apparent that simultaneously providing good visibility to both drivers of two opposing vehicles remains a problem for automotive lighting. There are many ways that drivers attempt to solve this problem, some more effective than others, but all pay a price. Until a means whereby parts of the headlight beam can be dimmed as necessary, particularly those parts of the beam that are illuminating the opposing driver, the balance between glare and visibility is likely to remain a problem.

Spotlight

20 ways of dealing with glare

When driving at night I dislike approaching undipped headlights. My wife feels irritated driving in daylight when the sky seems too bright. Driving instructors recommend avoiding looking directly into the headlights of an oncoming car.

Glare can be painful, disabling or both. Most of the time we just put up with it. But some of us have our own ways of dealing with glare. The following is a list of avoidance tactics. N.B. some of them are inadvisable and should not be copied.

Daytime

- Bright sunlight - use sunglasses on bright days
- Tunnel entry - close one eye a little before entering a tunnel in order to be adjusted (beware: loss of stereo vision!)
- Tunnel entry - many tunnels now have a threshold zone which adjusts the light levels gradually,
- Bright sky - when driving during the day use the visor to shield the eyes from the bright sky
- Bright sky - install a tinted screen or an external visor at the top of the windscreen
- Wet road reflection - shield the eyes with your hands to avoid reflections of the sun on a wet road

Dusk or dawn

- Low sun - shield the eyes with the visor or your hand against low sun rays
- Low sun flickering through trees lining road- shield eyes with hand or flip visor to the side
- Fog or Snow – reduce the glare produced by your own vehicle by dipping the headlights
- Fog or Snow – reduce the glare produced by your own vehicle by driving with just the fog lights (not permissible in many countries)

At night

- Other traffic - many people, particularly senior citizens, do not drive at night at all
- Other traffic - use special sunglasses (beware: loss of brightness)
- Headlights from behind - dim rear view mirrors (beware: loss of brightness in rear vision)

- Headlights from behind or the neighbouring lane – tilt wing mirrors (beware: some loss of rear vision)
- Headlights from behind – fit low transmission glass to rear window (not permissible in some countries. Beware reduced visibility when reversing)
- Oncoming traffic - dip headlights
- Oncoming traffic - remind the oncoming driver to dip his headlights by flashing your own (N.B. in many countries this is not legal)
- Oncoming traffic - avoid looking directly into the headlight of the oncoming car
- Oncoming traffic - close one eye a little before meeting the other car (beware: loss of stereo vision!)
- Following traffic - use handbrake when motionless to avoid glaring the driver behind
- Wet road reflection - Shield the eyes with your hands to avoid reflections of the headlamps on wet road

5 Automotive Lighting and Mechatronics

5.1 Introduction

5.1.1 Limitations of passive lighting systems

The evolution of automotive lighting systems is dominated by the basic design conflict between providing good visibility for the driver and avoiding causing glare for oncoming drivers. Taken to the extreme, good visibility for the driver can be achieved by allowing the headlights emit the maximum possible amount of light, while avoidance of glare is just the opposite: no light from the headlight at all.

In the past, the design conflict could not be solved in the true sense of the word. The only thing to do was to find clever compromises between the two conflicting design goals. The dipped beam lighting pattern is a good example of such a compromise (see Fig. 5.1). It provides good visibility by producing high luminance on the driver's lane, simultaneously avoiding glare for oncoming drivers by reducing the luminance on the other lane. Changes in the lighting pattern e.g. modifications of the exact form of the cut-off line, while modifying the compromise do not solve the basic design conflict.

It would of course be possible to define many other light distributions besides dipped beam and full beam. Thus other, possibly more intelligent compromises for specific traffic situations or weather conditions could be introduced. Fog lights are a good example here. But each additional lighting pattern reveals a further limitation of passive lighting systems i.e. the driver has to switch between different light distributions manually. Rarely do drivers switch in an optimal way, as most of us have experienced when encountering a car in oncoming traffic with activated full beam. It is interesting to note that many drivers hesitate to use the full beams, in case they forget to switch them off when oncoming traffic appears. As a consequence, the full beam is not used as often as it should be (Sullivan et al 2003).

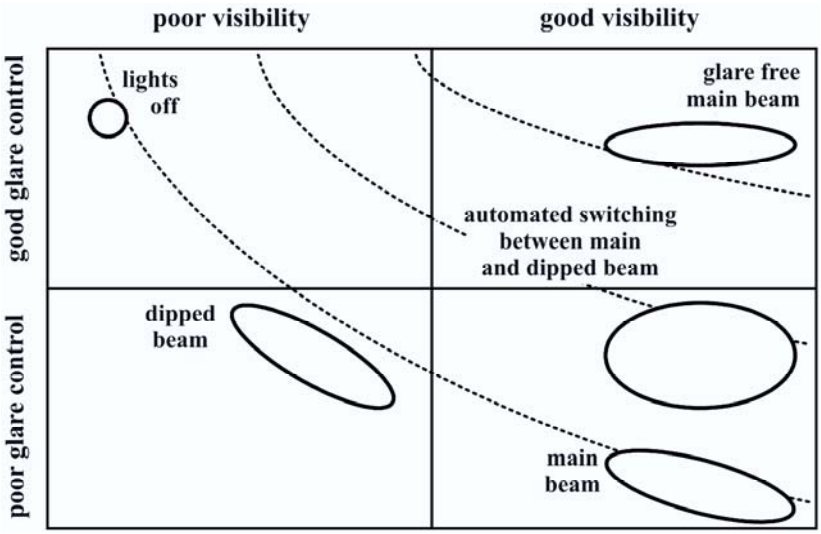


Fig. 5.1 Design conflict between visibility and glare control

Although the design of passive lighting systems has achieved a very advanced state-of-the-art, it can still be improved. Basic knowledge on visual perception has obviously not been taken into account in some cases: we know that humans can perceive contours much faster than they can perceive colours, but our signal lights still work with colour coding only. We know about change blindness, but our lighting systems still work in a simultaneous mode, lighting and highlighting all objects in the same way. We know about the disturbing effects of blinking emergency lights and about the high bandwidth capacity of our visual system for face recognition, but this knowledge is not reflected in present day automotive lighting technologies.

Mankind has always been creative in problem solving. So before we begin our exploration of new technologies, let us first have a look at lighting habits in the first spotlight.

Spotlight

Local lighting habits

It is a well-known fact that situations considered suitable for using the car horn vary in different countries. In India it is customary to inform the driver ahead acoustically when you intend to overtake. In Germany there are many towns where you are strongly discouraged from using the horn. The use of vehicle lighting also has a long tradition and habits do differ from nation to nation. It is interesting to highlight some of the differences not so much out of curiosity, but for the values encapsulated in the habitual use and their possible hidden potential.

European nations join in one lighting regulation

Vehicle lighting used to be something that each nation decided upon individually. Only in the late 50s did Europe begin to bring the interests of different nations together. This made it possible to drive one car easily through several European countries. It also suppressed some interesting automotive lighting solutions. For example:

- Town light - in Great Britain it used to be customary in towns to use running lights only. It was considered a nuisance to use dipped beams in urban areas where street lighting contributed adequate light for all road users. Particularly the glare of headlights was perceived as a grave danger in towns, because there were usually more pedestrians than cars. Pedestrians who were visible under street lighting would no longer be conspicuous if vision was impaired by the glare from headlights.
- Yellow headlights – in France headlights and fog lamps were permitted in yellow. The yellow light was considered to be more comfortable and better suited to adverse weather conditions. Particularly in foggy conditions the yellow light enhances the contrast of objects.
- Body language as indicator – in Great Britain attention was paid to the positioning of the car in traffic. For example, as you approached a round-about, you signalled to the nearby traffic which exit you intended to take mainly by how you approached the roundabout, which lane you chose and even how close to the lane markings you drove. It was not obligatory to use the turn indicator. The approach and positioning alone was a clear enough indicator.

Visual guidance

In order to drive a car, we need to know where the road is leading. It is necessary to know where the road is immediately in front of the car, where it is leading us and where we will eventually arrive if we follow its course. In daylight we can see the first few metres, and unless an object obscures our vision, probably also the next few hundred. At night this is not so easy. Some odd helpful habits have evolved in some parts of the world:

- Moonlight – in parts of South America, in particular the desert roads of Argentina, the long distance lorry drivers do not use their headlights at night if there is sufficient ambient illumination from the moon or the stars. They might just use their headlights to alert other drivers near junctions.
- Fog lights for better foreground lighting – high intensities in the foreground are usually undesirable as they may cause high adaptation thresholds. But if the headlights are deficient in foreground illumination the driver may feel insecure. The visual task of ‘tracking the road ahead’ benefits from good road markings. Illumination that clearly shows up the road markings in front of the vehicle allows easier path prediction. Drivers may therefore resort to their fog lights if the dipped beam of the car is deficient in foreground illumination. N.B. older drivers in particular find comfort in a wide and pronounced foreground illumination.

Colour in lights

There are many adverse driving conditions. As some of them are particularly severe in some parts of the world, it is not surprising that special solutions have been developed to deal with them:

- Snowploughs in Canada – snowflakes may cause as much reduction of vision as fog. The light from the driving lights is scattered back and dazzles the driver. Switching to full beam just makes matters worse. Backscatter from the headlights can be reduced if the line of vision is as far removed from the line of illumination as possible. But there seem to be other phenomena at work here. Drivers of snowploughs insist that yellow lights produce less self-glare and are better during heavy snowfalls.
- Road trains in Australia – driving on dirt roads can become particularly hazardous if you have to follow a road train through the Australian outback. The dust particles in the air scatter light back and lead to self-glare, thus obscuring what lies beyond. Lorry drivers in the outback tend to use green filters in front of the headlamp. Thus, the high reflectance in the shorter wavelengths for the typical reddish dust particles found is avoided and the good sensitivity of the eye in the middle, green wavelength is utilized.

Inverted shadows

During the day the outline of the car is visible mainly due to the high contrasts around its contour, which includes the shadow of the vehicle. At night this shadow tends to disappear. There is however one type of vehicle lighting which produces an ‘inverted’ shadow underneath the car:

- ‘Low glow’ or ‘under-floor lighting’ was allegedly invented in South America. Fluorescent tubes are applied to the underneath of cars, lighting up the ground on which they drive. The lighting is not intended to be a safety feature, but predominantly serves as a statement of prowess when curb crawling. Needless to say it was received with disdain, perhaps tainted by envy, by the general public and immediately outlawed in most countries. What is easily overlooked is the fact that the inverted shadow actually enhances the contour of the vehicle at night and (when applied in moderation) would actually lead to a safety gain for other road users.

Outlook

We have to cope with many anomalies when driving. The dangers lurking around the corner for the average driver in Australia will be different from those in Japan. It is worth learning from some of the habits highlighted by local lighting use. Supplying the right type of lighting for a particular environment can save lives.

5.1.2 Technology push

Tremendous developments in various technologies have changed the world in a way that was simply impossible to imagine, even a few years ago. Mobile phones are no longer considered a sophisticated piece of hardware. Notebook computers with the computational power for solving design problems in seconds (where ten years ago a team of engineers needed weeks of work) can be bought in the supermarket. Our cars are equipped with sensors of all kinds, GPS navigation has become standard and wireless communication allows us to access information on the traffic situation. The performance of LEDs is increasing steadily while DMD chips and mirror scanners are becoming cheaper and more robust at the same time. New sensor technologies such as the photonic mixing device are being developed. The big question is “How does all this affect automotive lighting?”

5.1.3 Solving conflicts with active systems

During the past few decades a general trend in the evolution of most technical systems has been the use of sensors, processors and actuators to give the systems a certain degree of intelligence and autonomy. This allows them to react to changes in their environment and to changes in the system itself. Electronic motor controls for example, use various kinds of sensors to sample information on ambient air temperature, motor temperature, exhaust gas composition and many other relevant variables. Fuel injection timing and volume are then adjusted to optimal values, depending on the actual situation.

But the most striking consequence of this development is that it was indeed possible to solve many design conflicts simply by adapting the system's behaviour to the actual situation. Antilock braking systems are a good example here. While it is desirable to achieve maximum deceleration during emergency braking, the wheels must not be blocked because of the concomitant loss of steering power. The conflict between maximum deceleration and steerability of the vehicle was solved by using sensory information on wheel rotation. The applied brake pressure was then reduced whenever a wheel was likely to be blocked. A passive system cannot easily be made to react to changing conditions. But an active system with its sensors, processors and actuators can easily adapt to the actual situation, finding optimal compromises between design conflicts for each individual situation. Further examples on how active systems have been used to solve design conflicts are:

- Active suspensions solved the design conflict between ride comfort and road grip
- Adaptive aeroplane wing cross sections solved the design conflict between lift and drag
- Electronic motor controls solved the design conflict between fuel efficiency and clean emission
- Active motor mountings solved the design conflict between vibration isolation and mounting stiffness

As all active systems involve sensors, processor and actuators, they can also typically be referred to as mechatronic systems and as such can be characterised and classified according to their energy and information flows (Isermann 2005).

5.1.4 The promises of active lighting systems

The basic idea of active lighting systems is to use information from the car, the environment and the driver, in order to adapt the lighting pattern to the actual situation. It is then possible to improve present lighting systems, by for example automatically switching between full and dipped beam – and possibly other light distributions – depending on the traffic situation (Wallaschek 1998). In addition, active lighting systems can also be used to provide more complex functions such as:

- Glare-free forward lighting: illuminating brightly the traffic space using the full beam provides good visibility for the driver. Glare for others is avoided by filtering out locally those parts of the light distribution, which could dazzle oncoming traffic or other traffic participants.
- Marker lights: objects of interest within the traffic space, such as street signs or pedestrians on or near the road, are specifically marked by rays of light directed to them.
- Display lights: context relevant information, for example individual direction arrows, is projected onto the road. Road signs can be selectively highlighted and optimal route guidance given.
- Co-operative lighting: the light distributions of all vehicles involved in a traffic situation are superimposed intelligently in order to obtain optimal conditions for visual perception. Road or tunnel lighting and vehicle lighting actively interact for the benefit of drivers.
- In an extreme scenario, active lighting could even be used to guide an observer's eye movements and thus his visual attention.

Although some of these perspectives are speculative, it is always worthwhile thinking about extreme scenarios because they suggest new ideas and directions for a somewhat mature technology. The lighting functions listed here will be discussed in more detail at the end of the chapter.

5.2 Automotive lighting systems from the perspective of mechatronics

5.2.1 Systems, energy, mass and information flows

Technical systems can be characterised by the energy, mass and information flows at their interfaces to the surrounding world. Before these flows can be studied however, what is considered to be part of the system and what the external world has to be defined. It is important to recognise that when we talk about a system, we often use this term to denote both the “real world system” and a “model of the real world system”. The latter is used to analyse and describe the behaviour of the former in an idealised and simplified way, by concentrating only on those aspects, which are of relevance in a given context, and neglecting everything else. In the analysis of its dynamic behaviour, the suspension of an automobile for example, might be described as a system of rigid bodies, which interact via spring and damper elements. This model takes into account only the inertia, compliance and damping properties of the elements, neglecting all other details such as the colour of the elements, their heat conduction properties or their aerodynamic characteristics.

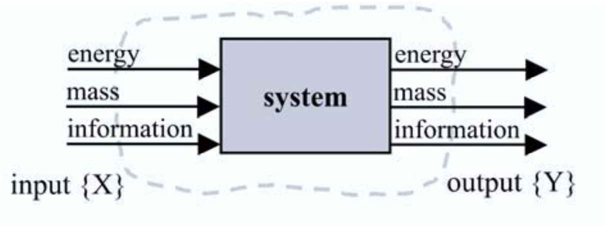


Fig. 5.2 System and its energy, mass and information flows

Fig. 5.2 shows a sketch of a system and its boundaries to the external world. The system interacts with the external world by input and output ports. These correspond for example, to points where external forces or e-lectrical voltages are applied, where masses enter or leave the system, or where information is exchanged with the system.

The energy flow for example, is described by electrical voltage and current, force and velocity, pressure and volume flow. Note that for each energy flow there are two variables, which enter its description. The set of all variables which are needed to describe the input and output of the system is denoted by {X} and {Y}.

A system’s behaviour can then be described by the relation that exists between the input and output quantities:

$$\{Y\} = f(\{X\})$$

This behaviour is also referred to as the “system function” or simply as the “function” of the system. In the context of system design methodologies, it is often desirable to describe the system function in a form, which is independent of the chosen design of the system. In other words it is advisable to define system structure, energy, mass and information flows in the most abstract way. For the purpose of detailed analyses, the system functions can often be stated explicitly in mathematical form (Lückel and Wallaschek 1997). For the purpose of synthesis or a description of the overall system behaviour, it might however be sufficient and more convenient to describe the system function verbally.

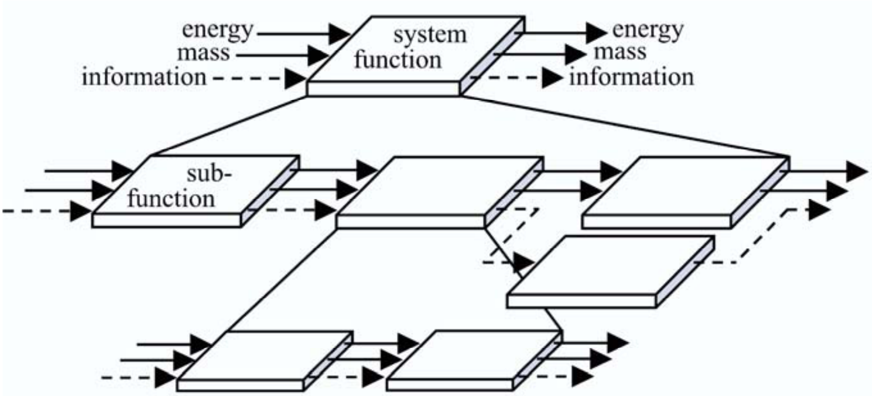


Fig. 5.3 Subdivision of a complex system into subsystems

Usually, complex systems are subdivided into simpler subsystems in order to obtain a modular and often hierarchical structure of the overall system. This allows us to reduce complexity to a level, which can be overseen by the design engineer and handled by state-of-the-art software systems.

5.2.2 System structure of classical headlamp systems

Fig. 5.4 shows two classical headlamp systems and a corresponding system structure including the relevant energy flows. The overall system function has been subdivided into the functions “generate light” and “form light distribution”. Note that each of these sub-functions can in principle be subdivided further. This can be continued until the most elementary description in the form of elementary functions like “transform electrical energy” or “reflect light” has been reached.

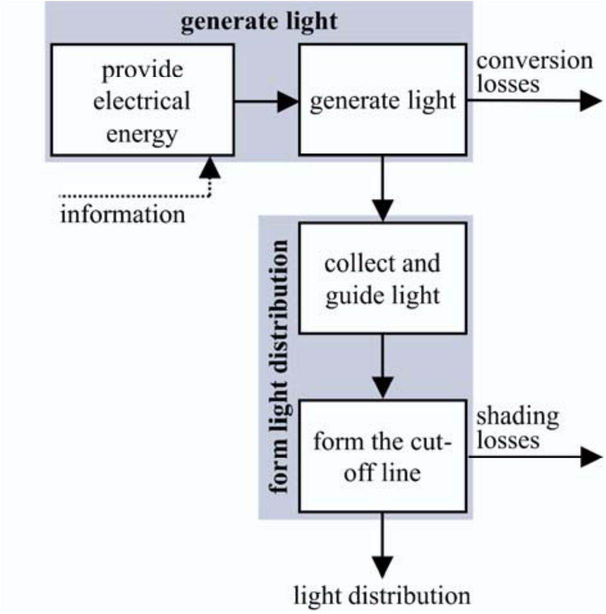


Fig. 5.4 Classical headlamp systems and their corresponding system structure

The cut-off line in the light distribution can be formed by using two different light sources, such as the two filaments in some halogen bulbs. Filament 1 is used for the full beam pattern. All rays are reflected by the paraboloid reflector and contribute to the light distribution. Filament 2 is used for the dipped beam pattern. A shutter is used in such a way that only rays, which are reflected below the cut-off line, reach the reflector. An alternative method could be to use only a single light source in combination with a movable shutter, as in the Bi-Xenon projection system. Here an ellipsoid reflector is used and a moveable shutter in the second focussing plane produces the desired light distribution. Both design alternatives serve the same purpose of providing two different light distributions. But the corresponding system structures are completely different, as can be seen in Fig. 5.5. Even without going into the details of the two solutions, we can immediately see the fundamental differences in the energy and information flows.

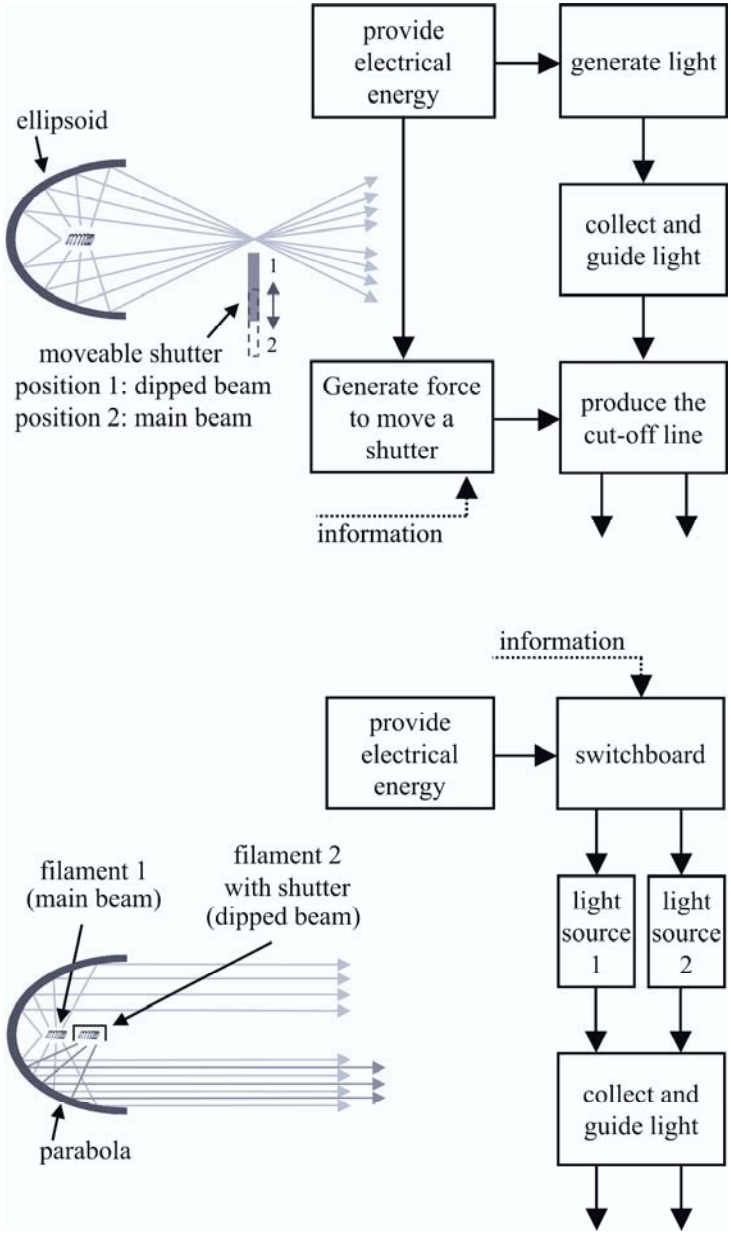


Fig. 5.5 Two alternative system structures for providing two different light distributions

5.2.3 Mechatronic systems

The basic idea behind mechatronic systems is to use sensors to capture information about the environment and about the system itself. This information is then processed and actuators are used to influence actively the system behaviour- by generating the energy or mass flows required for optimal operation of the system. The sensors and actuators act as an interface between energy and information.

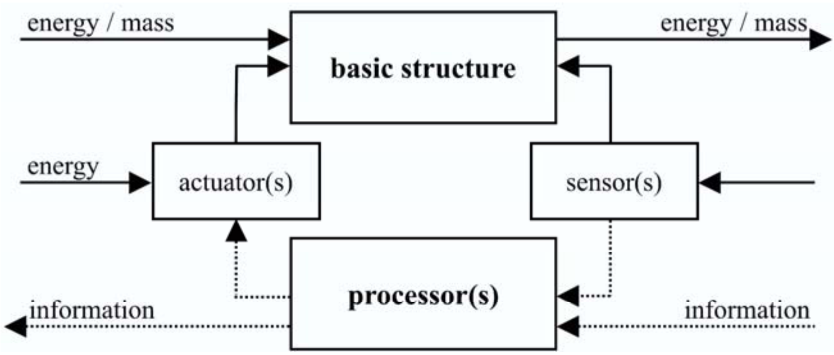


Fig. 5.6 General structure of mechatronic systems

Fig. 5.6 shows a simplified sketch of a mechatronic system. In one sense the basic mechanical system can be seen as an analogy to the skeleton of the human body. Here the sensors can be regarded as the sensory organs, the actuators are the muscles and the processors are the brain and central nervous system.

The actuators are used actively to determine the energy flows in the system, depending on the actual situation of the system and its environment. Sensors provide the necessary information about the system and its environment, for the processors to interpret the situation and decide on appropriate actions. These actions can for example, be given by the feedback signal of a controller algorithm, or by the activation of a shutdown process for the system, should a diagnostic algorithm detect a serious malfunction.

Depending on the level of information processing in such a system, we can further distinguish between “classical” and “intelligent” controller schemes. For classical controller schemes the processor executes a classical feedforward or feedback control algorithm. For intelligent controller schemes more sophisticated operations must be performed by the processor, such as pattern recognition, parameter identification or complex signal analysis algorithms.

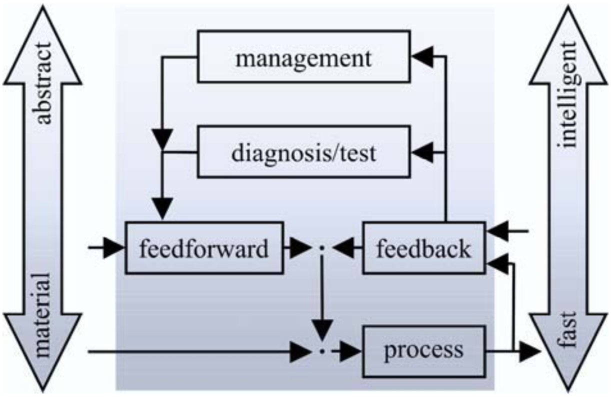


Fig. 5.7 Hierarchical system structure

The interesting thing about the general structure of mechatronic systems is that they have a dedicated interface to information processing, which allows the building of powerful hierarchical control systems. These systems might use access to databases for case-based reasoning, as well as other techniques from artificial intelligence that can be used to provide a certain level of cognition to the system (Rzerski 2003). Fig. 5.7 shows a sketch of a corresponding system structure. The high-level system functions such as diagnosis or reasoning are generally realised not by hardware, but by software. The low-level system functions on the other hand, are generally dominated by material aspects such as the dynamics of the basic system or the available sensor and actuator technologies.

5.2.4 Basic system structures for automotive lighting

There are four basic system structures that can be used to illustrate the existing possibilities for improving automotive lighting. Let us start with the situation depicted on the left in Fig. 5.8. The objects on the road are illuminated by natural light as well as the luminance of the surroundings. The only visual information that the driver can use stems from ambient light.

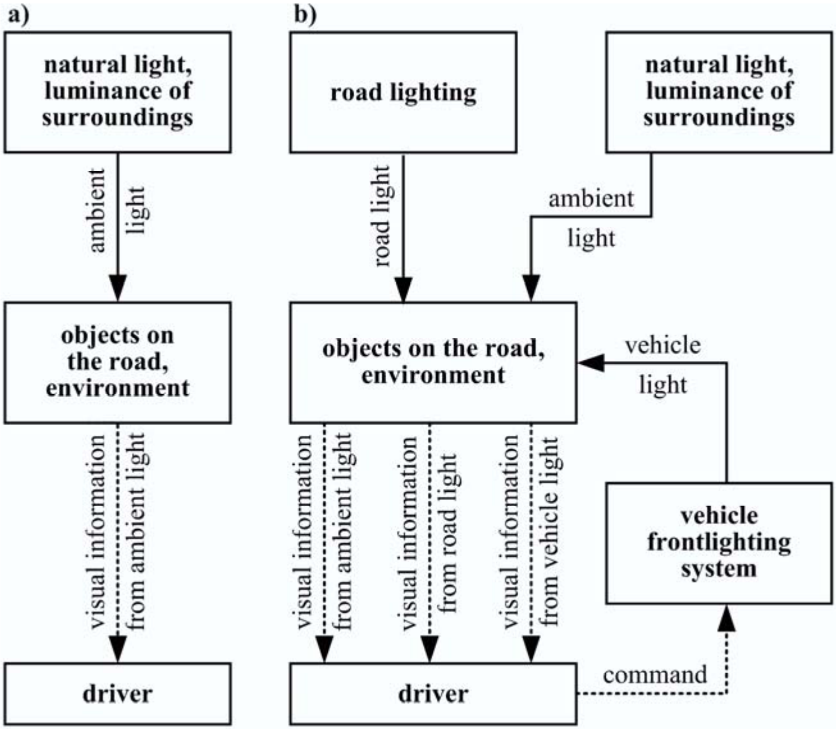


Fig. 5.8 System structures for (a) ambient light only and for (b) ambient light, road lighting and vehicle front lighting. Energy flows are shown as bold lines, information flows by dotted lines

On the right in Fig. 5.8 we see the system structure if vehicle front lighting and road lighting are taken into account. Note that there are now three energy sources: the luminance of the surroundings, including natural light, and the light distributions generated by the headlights and road lighting. The system does not adapt to changing environmental conditions. The driver obtains the information that he needs to drive the car by visual perception. The basic task of a passive front light system is to contribute additional light to the scene. It literally throws additional photons into the environment in order to provide additional visual information for the driver. Even if the driver changes the light distribution by switching between different states, this system is of a passive type.

It is clear that even in the basic passive system, further improvements in the visual information for the driver can be achieved, if knowledge of visual perception is taken into account in the design of the vehicle front-lighting system. Of course it is also possible to improve the situation with better road lighting.

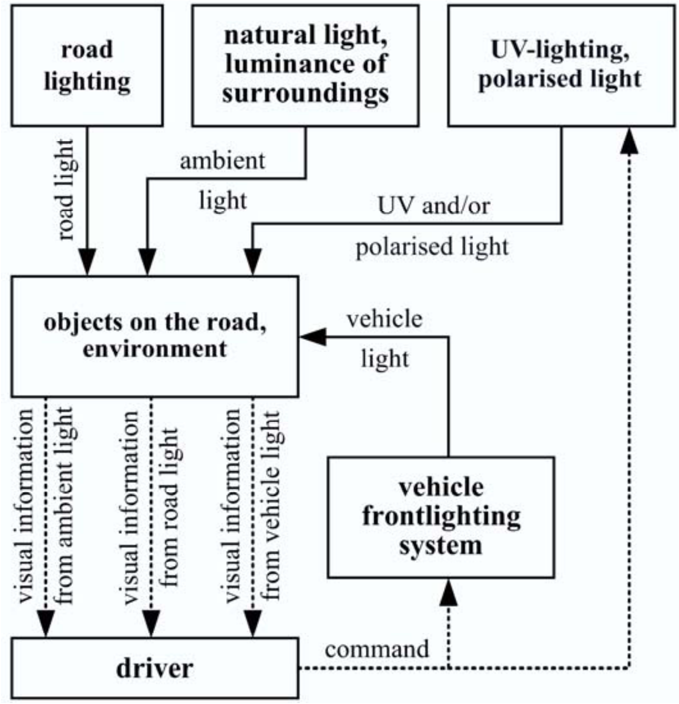


Fig. 5.9 System structure including additional lighting by UV-light or polarised light

Another way to improve the driver's visual perception of is to use "special" photons in the form of polarised light, or even to use radiation from outside the visible range. UV light for example is converted into visible light when it hits appropriate materials, thus adding visual information to the scene. The corresponding system structure is shown in Fig. 5.9. The system is still of a passive type, as – except for the action of the driver – no information on either the lighting system, the vehicle or the surroundings is taken into account.

Before we continue the discussion of lighting system structures from the point of view of mechatronics, let us first take a short but very informative detour on lighting in the ultraviolet and infrared range of the electromagnetic spectrum.

Spotlight

Lighting without glare

Light has the properties of being invisible in itself and only visible by its effects, for example by means of illumination. Lighting is troublesome in that it tends to cause the undesirable side effect of glare. In night time traffic the observer is himself part of the scenery. The headlamps illuminate the surroundings and inadvertently also tend to illuminate other drivers. Headlight design is governed by the compromise between seeing much and glaring little. The search for a lighting system without compromises has been started by many. This search -rather like the alchemists'- has borne fruit, but not necessarily in the expected areas. Three of the most recent findings should be mentioned here: polarised, ultra-violet and infrared light.

Polarised light

Polarisation is one of the wave properties of light. The polarisation plane is the plane in which the wave oscillates. Sunlight or the light from headlights has no preferred polarisation. Polarisation filters absorb most waves, transmitting only those of a preferred polarisation plane. Two polarisation filters next to each other, with polarisation planes at right angles, will absorb all waves. As an example, many modern sunglasses are made of material with the properties of a polarisation filter; sunlight reflected from the surface of water tends to be polarised: using the right filter orientation the sunglasses can cancel out the light reflected from water.

In the early 70s research showed that headlights could be designed to emit polarised light. Two potential benefits made an application interesting:

- If all drivers wear polarisation sunglasses or all cars have polarising windscreens then glare can be greatly reduced, while maintaining illumination at the level of main beams
- Glaring reflections from wet roads would also be reduced significantly

The experiment never found widespread application as the cost and timing for retro-fitting the complete fleet of vehicles and adjusting the infrastructure was prohibitive. Also, driving with 'sunglasses' at night may minimize glare, but significantly raises the detection threshold for all other objects.

Ultra-violet illumination

Ultra-violet rays (UV) are invisible to the human eye. Fluorescent materials exist however, which start to fluoresce in the visible spectrum when illuminated with ultra-violet rays.

Incandescent light sources generate only negligible amounts of UV. Research in the late 80s and early 90s showed that with modified gas discharge light sources, sufficient ultra-violet light could be generated for UV headlights. Test tracks with fluorescent road markings were prepared. The visual effect was startling. The road ahead seemed to be marked with luminous road markings, which appeared in tones of greenish-yellow. Many everyday items of clothing showed up under UV light. Rumours of reindeer with fluorescent fur abounded, but later turned out not to be based on fact! Again it was the cost of the infrastructure, new road markings, the quick deterioration of the fluorescent pigments and unknown health risks that delayed and finally quashed a widespread introduction of UV lighting.

Near-Infrared lighting

Infrared rays (IR) are invisible to the human eye. Cameras however, can pick up scenery illuminated with infrared rays.

Incandescent light sources generate IR well. Infrared light-emitting diodes and laser sources also exist. There is no shortage of infrared light as it is a natural by-product of thermal light sources. With the aid of a camera and display, a picture of the infrared scenery can be portrayed.

In the late 90s research investigating the potential use of near-infrared lighting for use in cars intensified. Systems were prepared that illuminated the field in front of the vehicle with an infrared high beam. A display in the vehicle showed the driver the view in front of the car. The advantages of the night-vision system thus created seemed apparent: without glaring the oncoming traffic the display was showing what amounted to a view of the road in front, illuminated by a main beam. A considerable amount of further research proved that responsible use of a night-vision system enhanced safety.

Far-Infrared

All warm objects radiate infrared rays at the far-infrared end of the spectrum (F-IR). F-IR is invisible to the human eye, but can be picked up by special cameras. With the aid of such a camera and a display, a picture of the scenery in the far infrared spectrum can be portrayed. Night-vision systems using this approach are well known from military applications and are also used by hunters. In the late 90s the first car piloted the use of far-infrared night-vision systems for peaceful use. Depending on the sensitivity of the camera and the temperature gradients in the scenery, the images generated give fair warning of obstacles on the road. Without the requirement for illumination, the image is not limited in angular resolution and can pick up objects far ahead. Initial concerns about the unnatural appearance of the images, due to potentially inverted contrasts e.g. a warm body may appear bright in front of a cold road, turn out to be of little relevance in everyday use.

We will now continue the discussion of general system structures for automotive lighting.

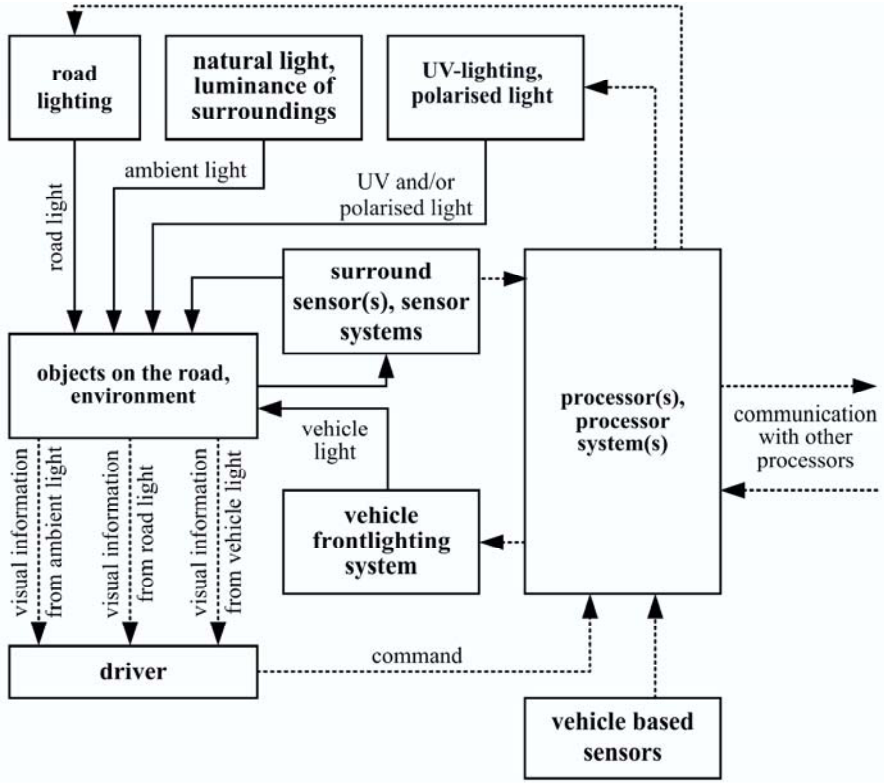


Fig. 5.10 System structure of an active lighting system

The structure of an active lighting system is shown in Fig. 5.10. Surround sensors or sensor systems are used to sample information on the environment, and vehicle based sensors provide information on the vehicle itself, such as speed, steering angle etc. The appropriate sensors and sensor systems will be discussed later in a special section. Some of them, such as an infrared night-vision system or a radar system, might use additional radiation to scan the environment as depicted by an arrow in the system structure.

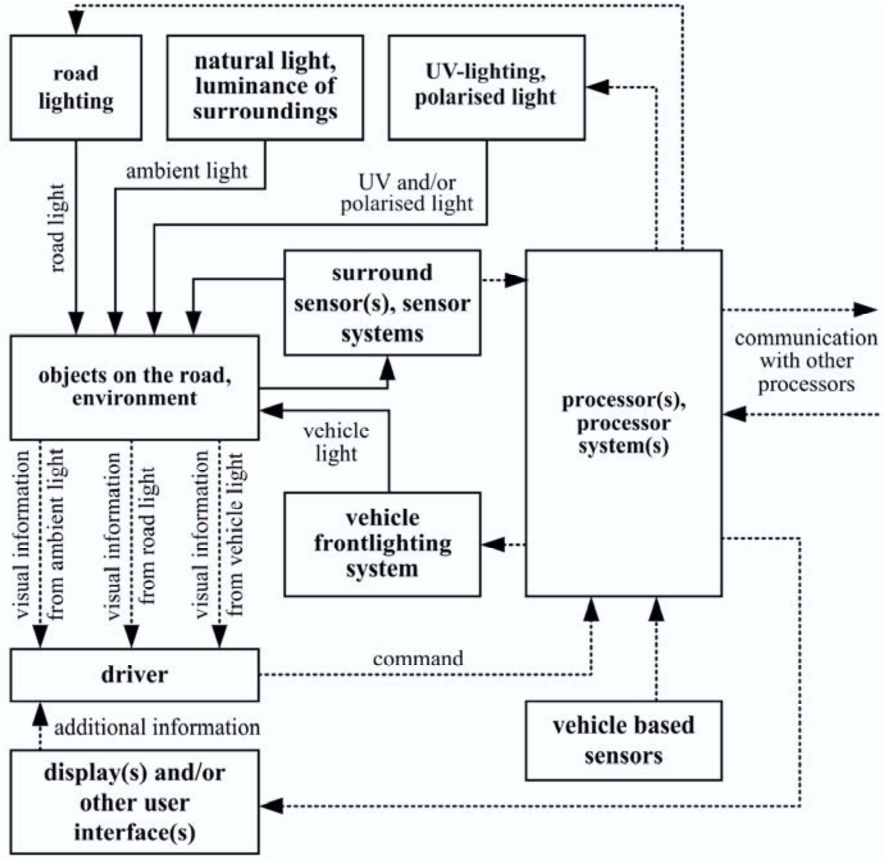


Fig. 5.11 System structure of an active lighting system with additional perception channel for the driver

The automotive front-lighting system, which is now capable of providing lighting adapted to the environment and actual traffic situation, can be of a classical type, such as the bending light where a conventional headlamp beam is simply rotated by an actuator so that the light distribution follows the road. It might however, be of a completely different design, as in the case of pixel light, where a digital micro-mirror device is used to form the light distribution (Enders 2001). The various actuators and optical concepts that are important in the context of active lighting systems will be discussed later in a special section of this chapter.

It is interesting to note that the processor not only commands the vehicle front-lighting system, but can in theory also be used to give commands to street lights, thus allowing simultaneous adaptation of the vehicle and road lighting to the traffic situation and/or to weather conditions. The processor also allows accessing of remote information e.g. about traffic, and it can even give feedback on the proper operation of the lighting system to an overall diagnosis system.

Both the passive and active lighting systems, whose structure has been shown in Fig. 5.9 and Fig. 5.10, rely on the driver's visual perception of the real world. Vehicle and road lighting are only used to improve the conditions for visual perception, but do not add additional channels of information to the system. A completely different approach to improve the driver's perception is to use additional displays or other user interfaces as shown in Fig. 5.11. In the case of a navigation system, a display might be used to indicate in which direction the driver should steer his vehicle at the next street crossing. The information can be presented in the form of directional arrows, as a marked trajectory on a map, or even as spoken words, such as "take the next exit to the right and follow the road for 100 m". The important point being that other perception channels are used, beside the visual one linked to objects in the real world.

It goes without saying that the system structures discussed here are not only used to visualise the overall structure of a system, but also form the basis for a more detailed mathematical analysis of the system. To this end the relevant energy and information flows have to be expressed as functions of the state variables of the system. The functions of the individual subsystems have to be formulated mathematically, the resulting equations analysed and solved by specific algorithms. We will not however, go into the details of that process here, but instead investigate the different possibilities of improving the present situation in automotive lighting. To this end we will answer the following questions:

- Which possibilities exist that could improve classical passive lighting systems by adding just a touch of mechatronics?
- Which system topologies and which sensors and actuators can be used in active lighting systems, and what progress can be made by using active lighting?
- What are the opportunities and risks of using additional channels of perception? Which technologies can be used in this context?

5.3 Simplify your life Improving passive lighting by adding just a little touch of mechatronics

5.3.1 Switching the lights on and off automatically

Mechatronics need not be complicated. It could indeed simplify your life! Remotely-operated central door locking systems, electric windows and sunroof, and electric seat adjustment are examples showing that even small steps in the direction of mechatronics can make a big difference in the everyday use of technical systems.

Many drivers worry about inadvertently leaving the headlights turned on when parked. In most people's past experience this has probably caused battery discharge and the vehicle would not start again. If the lighting system is equipped with a controller and has access to information on the vehicle status, it is only a small step to turning the lights on and off automatically.

In the simplest case, the function is limited to detecting when the vehicle is parked and the motor turned off, and then switching off the main lights, and at dusk activating the parking lights.

In a next step the lighting can be switched on automatically, when the illumination by ambient lighting is below a certain level, and switched off when it is above another threshold level. This function requires information on the level of ambient light, which can be obtained using an illuminance sensor integrated in the windscreen, as described in a later section. In certain "low-contrast" situations, like fog or heavy rain, these systems are not yet fully dependable, and should therefore be used in combination with daytime running lights only.

Finally, the lights can be activated remotely when the driver returns to his car, which might be parked in a large car park. What a lucky driver he is, if he can find his car by simply pressing a button! And how much luckier if the headlights of his car are not immediately switched off after he turns the keys or locks the door, but instead light up the path to the door of his home…

Lighting functions of the type described here can be found in most cars today. They all became possible by adding just a little bit of mechatronics to the lighting system, with the goal of simplifying our life.

5.3.2 Headlamp levelling

If you meet a car in oncoming traffic and are dazzled by its lights, then either it has turned its headlights on full beam, its headlights are not adjusted correctly, or it is an old car without a headlamp-levelling system carrying a heavy load in its boot.

Fortunately today, most cars do have headlamp-levelling systems. These systems use information on the vehicle status, which is sampled by sensors, and they use actuators to adjust the inclination of the main axis of the headlamp to the proper value.

Static headlamp-levelling systems typically use DC motors as actuators, while dynamic headlamp-levelling systems require more powerful motors. Fig. 5.12 shows a typical example of an actuator used in a present day dynamic headlamp-levelling systems. It consists of a rotary stepper motor, which is operated in feed-forward mode, and a spindle mechanism to transform rotary to linear motion. The rotor position, and thus the orientation of the headlight, is determined by counting the steps of the motor.

Fig. 5.12 Actuator of a headlamp-levelling system

The following spotlight on headlamp-levelling systems concentrates on the sensors and control algorithms used in these systems.

Spotlight

Compensating for a heavy load, sharp braking or accelerating, by headlamp-levelling systems

Introduction

The most important light distribution for driving at nighttime on country roads is the dipped-beam. It consists of two areas divided by the cut-off line. There is a bright area below the cut-off line offering the driver sufficient light and a dark area above the cut-off line to avoid glaring oncoming traffic.

Regulated by European law, the headlights have to be adjusted so that the level of the cut-off line declines with the distance to the car. The slope of the cut-off line is $\tan \beta_0 = 1\ \%$.

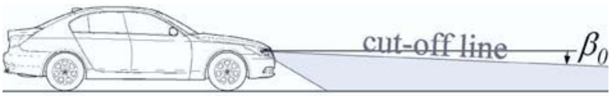


Fig. 5.13 Adjustment of the headlights

With a heavy load in the boot or during acceleration, the car body pitch counteracts the slope of the cut-off line and in extreme cases, the oncoming traffic can bedazzled by the high luminous intensities in the bright area of the light distribution. If the driver brakes, the slope of the cut-off line becomes steeper and leads to a short range of the headlights.

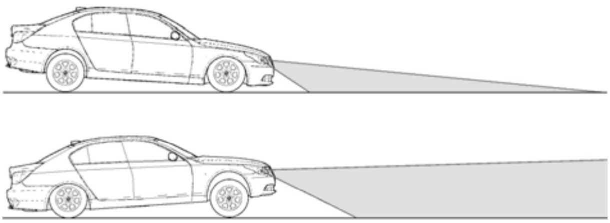


Fig. 5.14 Influence of the car's pitch angle on the light distribution

Quasi-static headlamp-levelling systems

Since the early nineties, new cars in Europe have to be equipped with a manually controlled headlamp-levelling system, to avoid the dazzle caused by a static pitch angle of the car body. The adjustment is usually made manually by the driver using a thumb wheel in the dashboard.

After the introduction of high-intensity-discharge (HID) lamps for cars, the manual adjustment of the headlights by the driver was no longer considered to be sufficient and automatic headlamp levelling became mandatory for cars with HID lamps.

Most levelling systems use sensors at the axles for the detection of the spring deflection, which is then used to calculate the pitch angle of the car body.

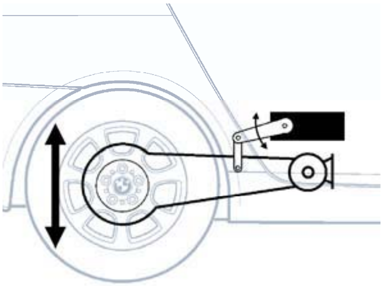


Fig. 5.15 Sensor for detection of the spring deflection at the rear axle

In order to eliminate the components of the sensor signals that are caused by ground waves, the control unit of the system uses dedicated data-smoothing algorithms. In this way only quasi-static pitch angles are compensated, like those caused by a load in the boot.

Dynamic headlamp-levelling systems

Today, dynamic headlamp-levelling systems can be found in nearly all cars equipped with HID lamps. Here the control also compensates the short-time dynamic pitch angles caused by the driving dynamics, aerodynamic and other effects.

Beyond information gained from the sensors in the chassis for the detection of spring deflection, additional information such as the speed of the car, or the acceleration and deceleration are used in the control of the levelling system. While driving at constant speed, the levelling system applies strong damping on the data. During acceleration or deceleration of the car, the damping is reduced in favour of obtaining a sufficiently fast response of the headlights to the changed pitch angle of the car body.

The proper choice of the amount of damping during braking or acceleration requires a compromise between interferences from ground waves and a fast headlight response to changing pitch angles. If the damping is set to a low level, the system shows a fast response, but ground waves can interfere with the motion of the headlight. If the damping is set to a high level, the disturbances from ground waves can be eliminated, but the response of the system will be rather slow.

A model- based approach to headlamp levelling

To overcome the shortcomings of the classical approaches described above, a different way to use the acceleration and deceleration signals for a dynamic headlamp control has been suggested (Bertram et al 2000; Lehnert 2001):

On the basis of an idealised car model, the acceleration and deceleration signals can be used to estimate the pitch angle of the car body. This method requires an explicit model of the vehicle dynamics and applies classic control and estimation methods to the problem of headlamp levelling. Thus a fast headlamp control without any interference from ground waves can be realised.

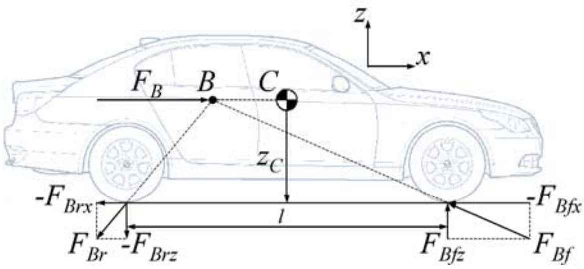


Fig. 5.16 Additional forces during braking or acceleration

Due to the vertical distance z_C between the centre of mass C and the contact point of the wheels on the road, every braking or acceleration force (F_{Bfx} and F_{Brx}) generates a pitch moment, resulting in a load shift from one axle to the other.

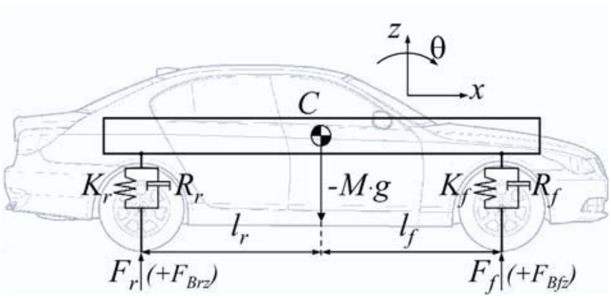


Fig. 5.17 Idealised car model

The additional vertical forces F_{Bfz} and F_{Brz} directly affect the suspension of the car and lead to the pitch motion θ:

$$\Phi_Y \cdot \Delta\ddot{\theta} = F_{Brz} \cdot l_r - F_{Bfz} \cdot l_f$$
$$M \cdot \Delta\ddot{z} = F_{Bfz} + F_{Brz}$$

The pitch motion changes the length of the suspension struts:

$$\Delta z_f = \Delta z - l_f \cdot \sin\Delta\theta$$
$$\Delta z_r = \Delta z + l_r \cdot \sin\Delta\theta$$

And the additional forces can be expressed as:

$$F_f = -K_f \cdot \Delta z_f - R_f \cdot \Delta\dot{z}_f$$
$$F_r = -K_r \cdot \Delta z_r - R_r \cdot \Delta\dot{z}_r$$

These equations only give a very simplified description of the vehicle dynamics. It does not yet for example, include the effect of the trailing arms at the axles of the modern chassis, which reduce the pitch motion of the car body (Matschinsky 1987). Nevertheless, the equations give an impression of how to describe the dynamics of the vehicle for the purpose of control of a headlamp levelling system.

Outlook

In dynamic levelling systems, the headlight is made to move in the vertical direction. In Bending Light, first introduced in 2003 for dipped beam, the headlights are made to move in a horizontal direction. In cars with both light functions, the headlights must consequently be fully movable in two directions. Such headlights would then not only serve their purpose in headlamp levelling or bending light, but in addition would be the perfect basis for the development of further light functions.

One new function is the adaptation of the dipped beam to the vertical curvature of the road, as proposed by (Kuhl 2006). The adaptation is brought about by lowering the headlights on road crests and by raising them in dips. The function promises the following advantages:

- reduced glare for oncoming traffic on crests
- increased range of the low-beam in dips

The more the movable headlights are adapted to the actual driving situation e.g. to the pitch angle of the car, to the curvature of the road or to the position of other traffic participants etc., the better the conditions of perception for drivers will be. This will lead to more safety and comfort as well as to a reduced accident risk during trips at night.

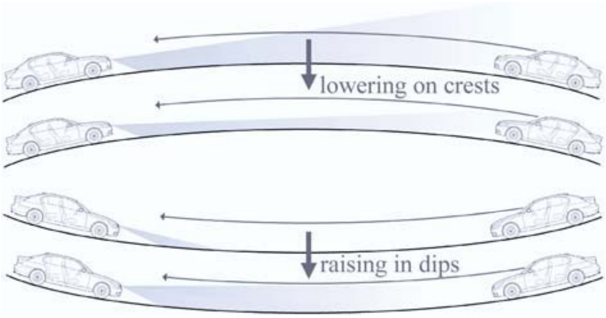


Fig. 5.18 Adaptive headlamp-levelling system

5.3.3 Dynamic bending

The first vehicle with dynamic bending light was the Citroen DS21. It was equipped with a mechanical linkage that coupled the steering wheel angle to the rotation of the headlights. This purely mechanical solution had the disadvantage that the light was directed into the curve only after the vehicle had already entered it. The system therefore did not find widespread use, and finally became obsolete. The idea of dynamic bending lights was later realised using electric motors as actuators to swivel the headlamp in its housing. Fig. 5.19 shows an example of a swivelling headlamp system.

Fig. 5.19 Swivelling headlamp module

To obtain the information required to calculate the command signals for the rotation of the headlamp axes, early systems only used vehicle-based sensors. The rotation of the headlights was controlled as a function of the steering wheel angle. Vehicle speed in combination with the lateral acceleration and/or yaw rate was also used to determine the local curve radius. Again these systems rotated the headlights only when the vehicle had already entered the curve. Like the purely mechanical system in the Citroen DS21, they do not allow the use of the dynamic bending light *before* the vehicle enters the curve. The next step in dynamic bending lights will therefore be to use surround-sensing technologies, to predict the most probable path of the vehicle and adjust the headlights accordingly.

Spotlight

Dynamic lighting

Introduction

Dynamic lighting is the movement of headlamp beams or the rapid changing of the dipped beam pattern, to improve visibility range and light distribution on the road and adapt it to the driving situation or the environment. With a few exceptions *static lighting* is still a standard for most cars. As static lights retain a constant beam pattern, the visibility range can sometimes be reduced significantly (sometimes down to 15 m), when the driver is braking or when he is driving into or out of a curve. Also the visibility range is far too short for driving on a motorway at high speed at night.

Dynamic lighting began with the introduction of dynamic levelling systems for Xenon headlamps in the early 1990s. Dynamic and Static Bending Light legislation was approved in 2003, after the first Advanced Front Lighting System (AFS) application. This allowed horizontal swivelling of the dipped beam (dynamic), or switching on and off of dipped beam contributors (static), to improve visibility in curves or when turning. So far all vehicle applications use a swivelling projector system, but swivelling reflector systems are also possible.

Control units and system topologies for dynamic lighting

Dynamic lighting requires moving components and actuators, driven by a control logic that receives inputs from various sensors. For most vehicle lines, Xenon and AFS systems are still options with a low consumer take rate (typically smaller than 20%). Only low-volume luxury vehicles reach consumer take rates of 50% and higher. Therefore the lighting control system of all existing systems today is still a completely separate unit, and is not integrated into the Body Computer or into other larger control units.

The first levelling control units worked with dedicated sensors to measure the suspension movement of the front and rear axle and vehicle speed. For diagnostics and calibration purposes, typically a K-Line serial bus interface was used. The motors (mostly stepper motors) were driven directly by the control unit.

During the last 10 years, most vehicles have introduced the high-speed network CAN (controller area network), to which most sensors and controllers have been connected. This allows the use of the same sensors in multiple applications.

The control units are typically mounted 1-3m away from the headlights, and the levelling/AFS stepper motors are driven with high frequency signals. The intrinsic problems with this topology, of radiated and conducted electromagnetic emissions, are difficult to solve. With the introduction of dynamic bending, a second stepper motor or brushless DC motor was introduced – causing even more radiation problems and increasing the cost and complexity of wiring. (Each stepper motor requires 4 power connections, so a total of 4 motors for a levelling and dynamic bending system require a total of 16 power connections). Therefore new topologies have been or are being introduced using serial networks.

Typically the AFS and levelling control remain within a dedicated control unit that acts as the *lighting control master*. This master still receives input through the vehicle High Speed CAN bus, but submits the control signals through a lighting bus. In some applications this is another - completely separate – lighting sub-CAN bus, but a growing number of applications start using a LIN (local interconnect network) bus.

Compared to the LIN bus, the CAN bus allows a much higher data rate (500 kBaud compared to 19.2 kBaud) and permits a Multi-Master structure, while the LIN bus only allows a strict one-master multi-slave architecture. But these potential advantages of the CAN bus are not required for lighting controllers. The LIN bus topology can be the better solution, as it saves system cost as given by the following components: the micro-controller (of Master and Slave), the quartz (higher timing accuracy required for CAN compared to LIN), and the wiring (CAN requires 2 lines, LIN only 1). A further cost reduction is possible by the introduction of a stepper motor driver with integrated LIN transceiver and control software. This ASIC (application-specific integrated circuit) allows the introduction of a ‘smart stepper motor’, i.e. with an integrated LIN interface, and eliminates the need for a separate slave micro-controller.

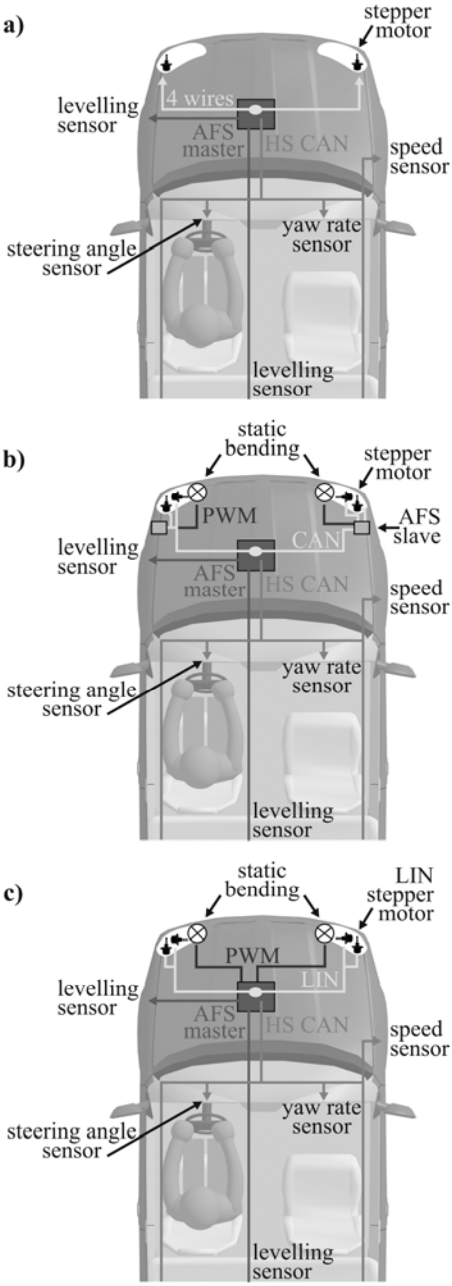


Fig. 5.20 a) direct motor drive, b) CAN lighting bus, c) LIN lighting bus

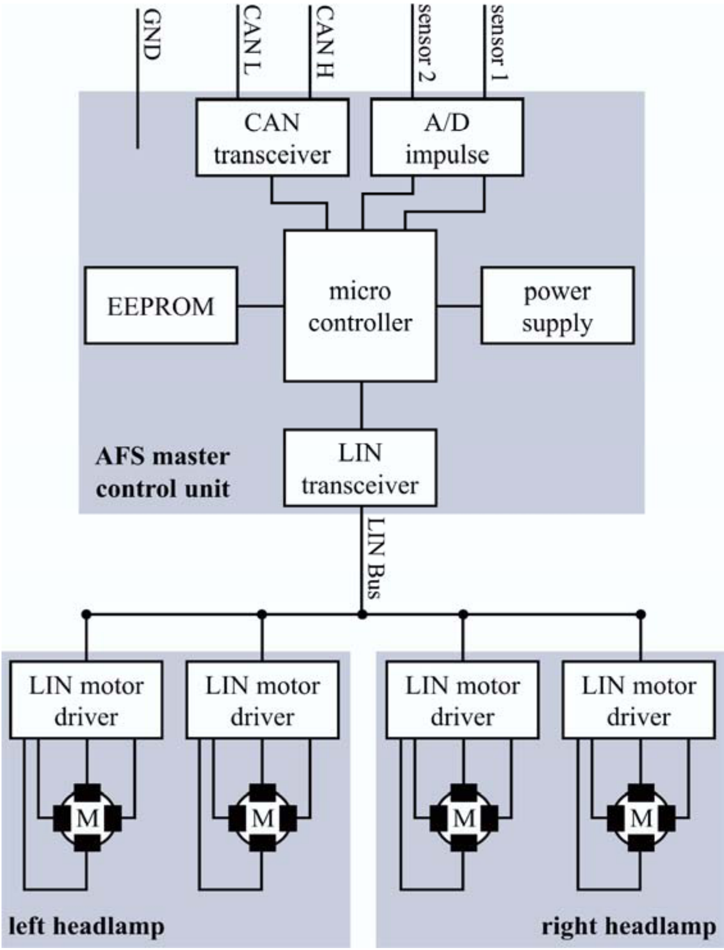


Fig. 5.21 Block Diagram of AFS headlamp control structure with lighting LIN Bus

Fig. 5.21 shows a block diagram of a typical AFS bending light control structure. All inputs into the control module are shown on the left side. Most inputs are transmitted through the CAN bus. In some cases dedicated sensors are still connected directly, if they are not required for other control systems.

The CAN bus is also used to calibrate the system, flash the micro controller with software updates or to diagnose failures.

In this case all output signals are transmitted via the LIN bus to the headlamps. Each motor is configured with a unique address, so that it can be controlled as a levelling or dynamic bending motor.

In a next stage, legislation for further AFS functions is expected to be approved by 2007. So far the dynamic and static beams have not allowed a change of the beam pattern. The new AFS functionality will allow just that and define 4 different beam types (basic, city, motorway and adverse weather beam).

An increasing number of vehicles offer AFS or Xenon headlamps, so that an integration of the control strategy into another body control unit will help reduce cost, complexity and packaging. More and more headlamps will be equipped with either intelligent actuators, or with lighting ‘slave modules’ that drive 2 or 3 actuators locally.

Outlook: Predictive AFS bending light

The integration of navigation system data into the AFS control strategy is a very promising development. Today's dynamic bending systems typically process steering wheel sensor and gyro sensor input, then calculate a swivelling angle of the dipped beam unit. To achieve an intuitive response and to fulfil ECE requirements, the algorithm also depends on vehicle speed. This behaviour of systems available today is not predictive and is independent of the vehicle environment. Future AFS functionalities such as motorway beam, will require additional logic to identify the driving environment.

Future navigation systems will provide information about road shape, road type and the ‘most likely path’ (MLP), and feed this into ‘predictive AFS systems (Ibrahim et al 2005). The MLP is that portion of the road ahead of the vehicle, which will be chosen with the highest probability, calculated from the road shape and driver inputs (e.g. if a driver does not reduce speed or use the turn indicator when he approaches a road branch, then “straight on” is the most likely path). Using new road data will introduce sufficient resolution to predict road curvatures ahead of the vehicle. This can be used to predict the optimal beam position on the road.

5.3.4 Interior light control

Initially interior lighting was restricted to the function of simply illuminating the interior of the car. A central lamp in the middle of the roof sufficed here. Later, additional lighting functions were added: reading lights, make-up mirror lights, entry and exit lights, and many more. Today, interior lighting is characterised by a large number of lighting functions and a considerable number of distinct light sources used to realise these functions.

The control of a large number of light sources and the design of the controls for functional lighting is a complex task. The use of programmable control units allows the finding of an acceptable compromise between simple and intuitive handling of the user interface, and the many possibilities to dim and adjust the individual light sources according to the drivers' and passengers' desires.

The development of LED and OLED technology has brought new possibilities for interior lighting. Using colour mixing of LEDs, the spectrum of the interior light can be changed. Warm white if the driver is excited, cold white if he is tired, red light if it is cold in the car, blue light if it is hot, just indicate a few directions for additional lighting functions for the interior. As many or most of these functions are related to comfort, they should always be seen in the context of other aspects of vehicle interiors, like ergonomics, climate and sound design. The design of aircraft interiors has led to first prototypes of lighting systems dedicated to relax and awaken passengers and compensate for jet lag. The next spotlight gives a more detailed treatment of interior lighting

Spotlight

Interior lighting – Not just a bright car interior

Interior lighting between design and engineering

The interior lighting of most current vehicle models comprises only the functions of interior and reading light. Materials, general impression and value are known to be major factors for the styling of a vehicle. Unfortunately, they are most often given maximum attention only when styling daylight design. Despite its great importance, night design is usually addressed insufficiently, if at all. Only a small number of models introduced in the past few years have used extended or improved light functionalities, to clearly demonstrate their top-of-the-range character even at night.

There is a strong trend towards improved interior lighting. Not only for styling reasons, but also from an ergonomic point of view, interior lighting is more than just illuminating the interior. Creating a fatigue-free environment, which allows the driver to concentrate on his driving task and at the same time enjoy his journey, is the ultimate goal of interior lighting.

But what is good interior lighting? What are the performance metrics for interior lighting? So far, only factors of visual capacity have been addressed, such as sufficient brightness and the avoidance of glare. In the future, other factors from the field of visual comfort and visual environment will also have to be taken into account. Thus for example, a visually pleasant distribution of brightness, different light colours including their effect on visual performance and well being, the specific use of shadows and the spectral distribution of light, are beginning to become major criteria for optimum interior lighting design.

Fig. 5.22 Concept of a luxury car interior lighting (Source: Hella)

Lighting functions for vehicle interiors

In the following, the individual interior lighting functions will be described in more detail. A classification of the different interior lighting functions can be done topologically i.e. using the positioning location (e.g. door, roof lighting). The classification can however, also be made according to the connection and wiring principles. Nevertheless, using the actual functionality of interior lighting for the classification has proved to be most effective, from a systematic as well as from a logical point of view.

- Entry/exit lighting: the entry/exit lighting supports the driver during entry to or exit from the vehicle. This lighting includes door warning lamps, the lighting of sills, door handles, the foot well and the area directly surrounding the vehicle. These lamps are primarily activated when the doors are opened.
- Orientation lighting: this term is used to classify the lighting of switches, door handles, safety belt mechanisms and other operating elements. Here, the easy and quick recognition of these operating elements must be guaranteed, but at the same time these lights must not dazzle and irritate the driver's eyes.
- Functional lighting: here light sources are switched on actively as required by the driver or passenger. Reading lamps, make-up mirror light or the lighting in the glove compartment or trunk are included in this category.
- Ambient lighting: is used to make the space inside the vehicle appear three-dimensional and offers the possibility of being able to perceive the surfaces and the interior as such, in addition to orientation lighting. For this reason, the criteria for ambient lighting are similar to those for orientation lighting. Typical areas of application are the lighting of centre consoles, foot well, B and C pillars and door areas.

Car drivers gather most of the information required during night-time driving from their field of vision which is directed forwards with an angular range of approximately 6°, and adapting to luminances of approx. 0.4 - 1.2 cd/m² when looking into the headlamp cone in front of the vehicle. Nevertheless, the information recorded by peripheral vision must not be neglected. This influence has been recognised and made the subject of ambient lighting - a new area of automotive lighting and important innovative field for technology and design.

Fig.5.23 Entrance/Exit light activated by remote door opener (Source: Hella)

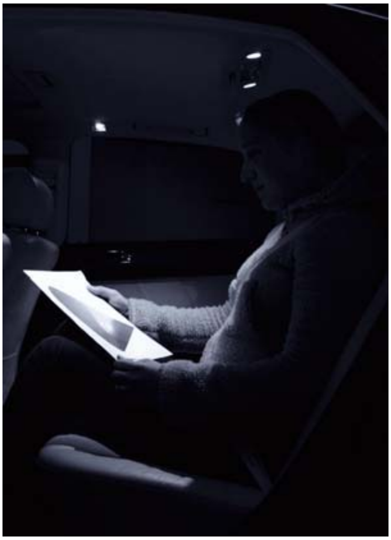


Fig.5.24 Glare Free Reading Lamp by small light outlets (Source: Hella)

Fig.5.25 Ambient lighting of a door panel (Source: Hella)

Ambient interior lighting has the function of conveying a pleasant "working atmosphere" to the driver. At the same time, there are a few physiological aspects associated with ambient lighting. Ambient interior lighting can significantly improve a driver's orientation in the vehicle, thus making a positive contribution to road safety. It must be remembered however, that the lighting inside the vehicle must never restrict the driver's attention and visual performance. In particular, the effects of the reduction in sensitivity to differences caused by veiling luminance on the windscreen must be mentioned here. In addition, if the luminances within the vehicle are too high, they produce a change in the adaptation level.

Light colour plays a significant role for the physiological and psychological impression of the vehicle interior, both for the driver and passengers. Having started with coloured lighting on the instrument panel, coloured light is now being used more and more by vehicle manufacturers for various ambient and orientation lighting functions, as a brand identification feature.

Chances and possibilities for future developments

A look to the future reveals the still huge potential for innovative vehicle interior light systems. The current demands for comfort, safety and differentiation/individualisation will continue to increase, so that optimally matched vehicle interior lighting will come to be considered a standard feature. Alongside design freedom however, various existing primarily technical constraints, limitations and developments must be taken into consideration. These can also result in innovative solutions based on sheer necessity and can accelerate their product launch. Thus for example, the steady reduction in design space in trims and support structures drives the search for low-profile light systems and solutions for specific light guidance for the integration of interior light components.

The availability and increasing performance of new light sources, in particular white LEDs, also open up possibilities for a wide range of applications in the vehicle interior. High-performance organic LEDs as large-surface and flexible light sources are already appearing on the horizon as an indication of the possibilities of absolutely new types of interior lights.

Dynamics and automation are further important terms related to future vehicle interior light concepts. Minimising the manual intervention required is the objective vital to reducing the strain put on drivers by the manual control of ever more varied interior lighting features, which in this form provide no comfort whatsoever! The minimum possible irritation of the vehicle driver must be achieved by means of the dynamic adaptation of a range of different lighting states.

Keywords such as "intuitive operation", "contact-less switching" or "adaptive interior light" point the way. The aim is to make those actions easier that do not directly serve the purpose of driving the vehicle. Intuitive interior lighting will be designed to take the strain off drivers at night and support them by specific interior lighting, optimally adapted to their visual performance and well being.

Summary

After long years of stagnation, the end of the 1990s saw the beginning of a very exciting development, which is dedicating more and more attention to the night design of vehicle interiors by means of light and lighting.

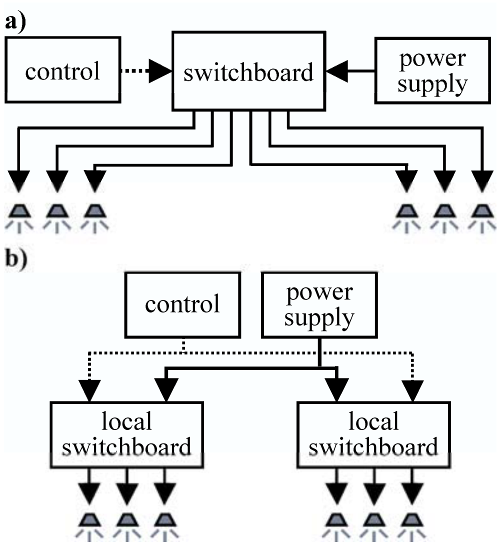


Fig. 5.26 Two different wiring concepts for automotive lighting.

5.3.5 Lighting bus and wiring

Even without adding additional lighting functions, which can easily be realised by a piece of software in the controller, the mechatronic system approach can offer a number of advantages. In a classical set-up, each light source was powered independently, the wiring being such that it connected the central switchboard with each of the lamps, resulting in a huge number of power line connections. The use of decentralised controllers and switchboards, in combination with a corresponding system topology, allowed the reduction of the amount of wiring, see Fig. 5.26. It is an interesting idea to go one step further and even use the same wires for both information and energy flow. But this form of power line communication turns out to be very sensitive with respect to disturbances and fluctuations of the automotive power network.

There have been attempts to introduce special communication buses for lighting, but they have not yet been fully successful. Most present day lighting systems either use the CAN bus or the LIN bus for communication. The communication bus and the local processors for the lighting system can of course also be used for diagnosis and test purposes.

5.4 Active lighting

The basic idea of active lighting is that – given the limitation of the overall light flux – it is probably better to direct the available light to those parts of the surroundings where it is needed for the visual perception of the driver. Instead of having the front lighting system throw its photons in an indifferent way, regardless of objects out there in the traffic space, an active lighting system tries to aim its photons as carefully as possible at those objects which are of interest to the driver. As everyone knows, a few single well-aimed shots are often much more effective than shooting pellets at random.

Fig. 5.27 gives an impression of how active lighting systems might work. It shows a photograph of a scene where those objects that are important for the driver such as stones on the road, traffic signs or road markings are highlighted, and the oncoming traffic is not dazzled.

Fig. 5.27 Active lighting

5.4.1 Sensors and sensor systems for active lighting

“Sense – Think – Act”. These are the three activities of intelligent technical systems. Sensors and sensor systems provide the senses for active lighting. They help the system to perceive its environment and its own state. If the lighting system is required to react to the presence of other vehicles and persons on the road, then these objects first have to be detected. If the light distribution is required to be adjusted to the type and topology of the road ahead, then these facts first have to be identified. In the following, we will give a brief survey of sensors and sensor systems relevant for active lighting systems. To this end, the driver’s environment is subdivided into 5 regions, depending on the distance to the driver’s body- see Fig. 5.28.

The first region is the vehicle interior, including the dashboard and everything the driver can reach with his hands. The second region includes the vehicle’s exterior and its immediate neighbourhood i.e. a region of several metres around the car. It is this region that must be surveyed when parking a car. The third region is that part of the traffic space lying within the normal visual field of the driver. It is the region in front of the vehicle, extending as far as the driver can see. During daylight, this region is limited by the natural horizon. At night it is usually limited by the illumination provided by the headlights. The fourth region is the area of the traffic space that does not fall within the visual field of the driver. It is the region behind and next to the vehicle. Finally the fifth region is that part of the world that the driver cannot see, the region which can not be explored by vision. Although this region is beyond the driver’s sensual perception, the driver might be interested in for example, the traffic situation or weather conditions 10 km ahead.

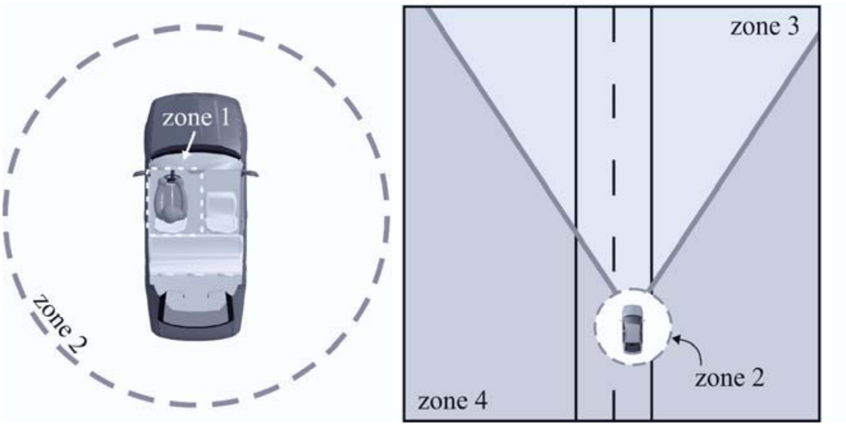


Fig. 5.28 The driver and his/her environment

In the following we will discuss available sensor technologies for the 5 different regions of the driver's environment, which are of interest for active lighting systems. Please bear in mind that the aim of these sensors and sensor technologies is to gain information that is useful in the context of automotive lighting. The list is far from being complete and just provides some typical examples.

Sensors and sensor systems for the driver and his/her immediate surroundings (zone 1)

The illuminance level in the interior of the vehicle can be a typical interesting piece of information in zone 1. It might for example, be useful for the control of a display. It might also be interesting to capture information on the driver itself. Whether he is fully awake or sleepy. In some extreme visions of active lighting, it might also be of interest to know where the driver is directing his glance, because this information could be used to adjust the light distribution accordingly.

Sensors and sensor technologies for zone 1 are:

- Eye tracking: a camera focuses on one or both eyes and records their movements. The point the person is fixing is then computed as a function of the eyes' position and orientation by triangulation. Usually the centre of the pupil is marked by creating corneal reflections of an infrared light source or an LED. This can even be mounted in the centre of the camera lens, and the fixation points can be displayed on a video image of the visual field. Typical sampling rates are above 30 Hz. Unfortunately, eye tracking systems are expensive, bulky and sensitive to disturbances. Today they are used in research projects rather than in everyday applications (Duchowski 2003).

- Photometric illuminance sensor: photo-diodes and photo-transistors can be used as light receptors. Often the light is filtered according to the spectral response of the average human eye. Illuminance sensors are low-cost devices, which find applications in the display control for mobile phones, personal digital assistants and notebook computers.
- Interior camera systems: camera systems in combination with image processing or pattern recognition may be used to detect the location of the driver, whether he is sitting in the correct position, or if there are other persons in the cabin (Cheng and Trivedi 2004). Their signals can also be used in order to estimate whether the driver is tired or not.
- Steering angle: the steering angle position can be measured using standard techniques such as a potentiometer or encoder. An interesting point is that the time history of the steering angle signal contains important information on the driver’s status. The amplitudes of the dynamic components of the steering angle signal become larger when the driver is tired, and the typical frequencies might be an indicator for the conditions of visual perception.

Sensors and sensor systems for the vehicle and its immediate surrounding (zone 2)

In modern cars, almost all information on the vehicle status is available via CAN bus, which networks all sensors and controller units in the car. Most of the sensors and sensor technologies listed below are not specific to automotive lighting, and have been introduced for other systems e.g. antilock braking systems, airbag systems, cruise control or others. The signals sampled by these sensors however, can be very useful for automotive lighting.

Sensors and sensor technologies for zone 2 are (Bosch 2004):

- Vehicle speed and angular speed: a wide variety of sensors exists. Rotational encoders at the wheel are most commonly used for measuring vehicle speed. Angular speed can be measured by gyroscopic systems consisting of a symmetric piezoelectric structure, which is made to vibrate in a resonant mode shape. If the structure is rotating, the Coriolis Effect causes a cross-coupling between the excited mode and another mode, which has the same resonant frequency but an orthogonal mode shape. A sensor electrode is used to measure the amount of cross-coupling and thus the angular velocity. Integrated sensor modules for the electronic vehicle stability programme, combining angular velocity and acceleration measurement in a single unit now exist (Barbour and Schmidt 2001).

- Acceleration sensors: acceleration can either be measured directly by using piezoelectric proof-mass sensors, or it can be calculated by differentiation of a velocity signal. Micro-mechanical sensors for both linear and angular acceleration are available for 1D and 3D motions (Marek and Illing 2002).
- Ultrasonic range sensors: these sensors send an ultrasonic signal and receive its reflections. The distance to the nearest obstacle is determined by timing the interval between sent and received signals. The use of ultrasonic range sensors is limited to small distances of a few metres only.
- Satellite navigation: GPS-based navigation has become standard technology in most travel pilot systems. It can be used to detect the absolute vehicle position to an accuracy of several metres. In combination with map correlation an accuracy of better than 1 m can be achieved. As an alternative to GPS the Russian GLONASS and the European Galileo system can also be used (Hein 2000).

Sensors and sensor systems for the traffic space in front of the vehicle (zone 3)

These sensors and sensor systems are most relevant for active lighting and most driver assistance and safety systems, such as adaptive cruise control and emergency braking systems. Their main task is to detect the presence of objects in the traffic space, classify them and locate their position and relative velocity. Based on this information, algorithms calculate for example the probability of a pedestrian crossing the street, or of a vehicle coming into collision.

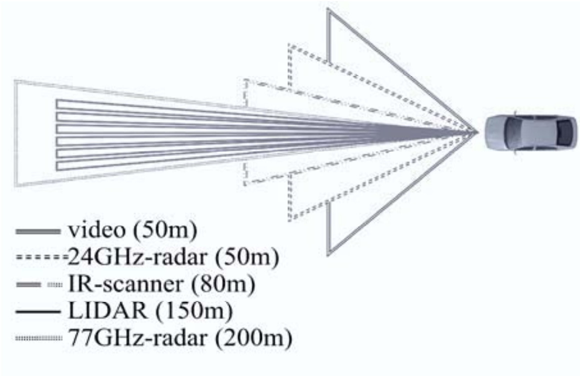


Fig. 5.29 Sensor systems for the traffic space in front of the vehicle (zone 3)

Sensors and sensor technologies for zone 3 are - see Fig. 5.29:

- Radar:
  Presently there are two different systems in use for automotive applications: systems working at a frequency of 24 GHz having a range of approximately 50 m, and systems with a frequency of 77 GHz covering a range of up to 200 m. These systems either use pulse-echo techniques for distance detection, or they work with a frequency modulated continuous wave (FMCW), which allows the simultaneous measurement of distance and relative velocity. The opening angle of radar systems for automotive applications is typically between 10° and 15° (Gresham et al 2001).
- Lidar:
  These systems work on the same principle as the short range radar system, except that they use infrared light as electromagnetic emission. The relative distance to the nearest object is determined from time of flight measurements. The maximum range of Lidar systems is approximately 150 m and the opening angle is approximately 15°.
- Infrared scanner:
  These systems work with a rotating pulsed beam. The reflection of an emitted laser pulse is detected and the distance to the respective object is determined by a time of flight analysis. The maximum range is approximately 80m with an opening angle of 120° or even larger (Kluge 2004; Nitsche and Schulz 2004).

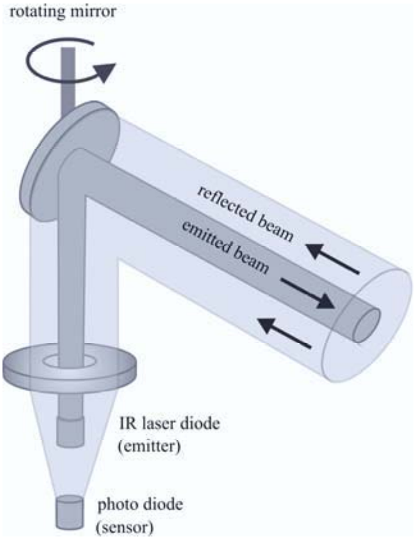


Fig. 5.30 Infrared laser scanner

- Camera systems:
  Image processing of video signals can be a powerful sensor system. Charge coupled devices (CCD) and complementary metal-oxide semiconductor (CMOS) chips are most commonly used. Due to their widespread use in many high volume markets, camera chips are small, powerful and cheap. Their resolution can be 1000 by 1000 pixels or even better. The use of stereo-imaging techniques allows the construction of 3D maps of the traffic space (Shan and Thomson 2004).
- Photonic mixer device (PMD):
  These systems use the reflection of intensity-modulated light and construct a 3D image of the surroundings. PMD sensors still have only limited resolution in the order of 100 by 100 elements and their range is limited to approximately 20m (Luan et al 2001).
- Infrared night vision systems:
  Passive infrared night vision systems detect the natural emission of objects in the far infrared spectrum. Warm objects appear bright on the picture, which looks unfamiliar at first glance. Active infrared night vision systems use an active near infrared light source to illuminate the scenery (Broggi et al 2004; Xu et al 2005).

State-of-the-art high class vehicles are already equipped with a large number of sensors for the vehicle state, including GPS systems for the determination of position. Some vehicles are even equipped with long-range sensors, such as lidar or radar systems. These sensors and sensor systems can be used for the purpose of active lighting at essentially no cost.

Sensors and sensor systems for the traffic space behind and next to the vehicle (zone 4)

Drivers should be aware of what is going on behind and beside their vehicle. It is however, difficult to observe these regions continuously. The main attention is on the traffic space in front of the vehicle. Side mirrors are small and have blind spots. It is therefore straightforward to use dedicated sensors to survey zone 4, which is outside the usual visual field of the driver. Based on this sensory information, specific assistance or warning systems, like lane departure warning or blind spot monitoring can be developed.

All sensor systems that are used for zone 3 can in principle, also be used for zone 4. Cameras included in the vehicle's rear can be used for a reversing or parking aid, and cameras in the side mirror can be used to monitor the overtaking lane.

Sensors and sensor systems for the remote world (zone 5)

Information about the remote world i.e. that part of the world which cannot be seen directly from the driver's position, can be very useful when driving a car. Examples are the knowledge of the best route to the destination point, or knowledge of traffic jams, accidents etc. Due to the tremendous progress in wireless communication, information becomes available anywhere, any time and at almost no cost. These techniques can of course, be used to provide the driver with important information for navigation and other purposes.

5.4.2 Actuators for active lighting

The headlights are the most important actuators of an active lighting system. They produce the light distribution for the illumination of the traffic space. There is a wide variety of novel optical concepts for headlamps that have been developed during the past few years. In the following we will report the most important ones (Kauschke et al 2003).

These optical concepts can be used in a stand-alone mode, when they are used to generate a light distribution in its totality. It is however much more interesting to think of them as a complementary addition to an already existing basic light distribution, generated by a classical headlamp. In such a hybrid system for example, the low beam could be generated using a standard headlamp, and the active part of the light distribution, which is generally restricted to a region between -1° and +4° around the cut-off line, could be generated using one of the novel optical concepts.

Headlamps with movable shutters and/or lenses

Active lighting is about modifying the energy flow provided by the light source. In the simplest case this can already be done by including movable elements, like a shutter in a classical headlamp. Movable lenses can of course, also be used.

Actuators that can be used to move these elements include (Börnchen et al 1999), (Pons 2005):

- Electric motors: DC motors and stepper motors are widely used in headlamp levelling and swivelling. They can also be used for moving shutters or lenses. Depending on the many kinematic concepts which are chosen for moving shutters, voice coil motors and electromagnets can be an alternative to classical motors (Kenjo 1991).
- Hydraulic and pneumatic actuators: these actuators allow the design of drives with high energy and force. But they are not common in automotive engineering and have thus to be considered as “exotic”.
- Shape memory alloys (SMA): solid state actuators on the basis of shape memory alloys have the highest energy density among all actuator technologies. Their use is however, restricted by the demand on a controlled thermal environment. In addition to that, the repetition rate of SMA actuators usually does not exceed a few cycles per second (Seelecke and Müller 2004).
- Piezoelectric actuators: these actuators have the highest power density among all actuators when they are operated at high frequencies. Their stroke is usually very small, while they can deliver large forces. Often specific kinematic designs for increasing their stroke are used. A particularly interesting type of piezoelectric actuator is the ultrasonic motor. Ultrasonic motors combine high positioning accuracy and high force densities with a theoretically unlimited stroke. Both linear and rotary ultrasonic motors exist (Hemsel and Wallaschek 2000), (Uchino et al 2004).

Before we continue the general discussion about actuators for active lighting systems, let us first learn about the details of one specific solution, the Bi-Xenon system.

Spotlight

Bi-Xenon: Actuators and mechanisms competing for their role in front-lighting

Introduction

In 2005, approximately 25% of cars bought new in Germany/Europe were equipped with Xenon front lights. A large number of them are projection systems, where a movable shutter is used to generate the cut-off line in the light distribution. The shutter is moved by an electromagnet- see Fig. 5.19.

Obviously this design has been very successful. The interesting question is, why at the end of a long design and prototyping process, this particular design evolved and not another one?

Fig. 5.31 Double filament (Bilux) light bulb (source: Osram)

Historical background

For several decades, the double filament (Bilux) light bulb has been the dominating light source for automotive lighting. It was initially designed to produce two light distributions out of only one reflector with only one light bulb but two filaments, see Fig. 5.31.

With the introduction of the Xenon discharge lamp as a light source for automotive lighting, the new challenge was: how can the new light source be used optimally in a front-lighting system with two light distributions?

A first obvious solution was to use two independent headlamps for dipped beam and main beam. But soon the aim was to have two light distributions from only one headlamp and only one Xenon light source. Although headlamp makers were highly interested in developing Xenon discharge lamps with two distinct arcs, it turned out to be extremely difficult to design such a system with two light sources. Thus the task of the engineer was further modified: how can two light distributions be generated from only one light source?

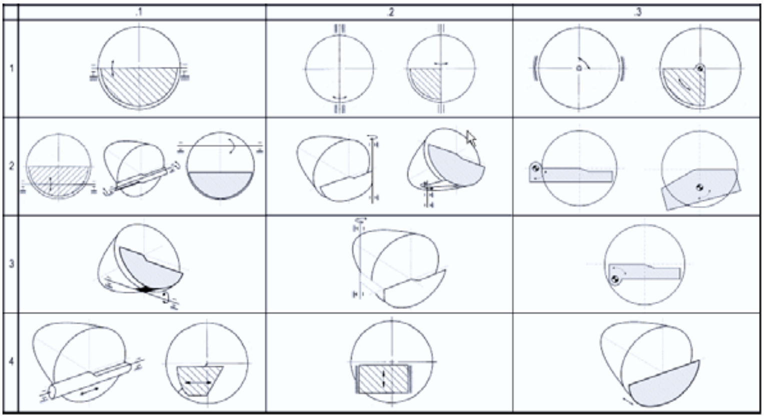


Fig. 5.32 Possible paths for the motion of the shutter (Börnchen 2001)

Design and actuation alternatives

If we consider classical headlamp designs, there are theoretically, three design alternatives:

- The light source can be moved relative to the optical system. This solution mimics the double filament (Bilux) light bulb, with one important difference: it is not possible to have both light sources operating in parallel.
- In a projector system, a shutter can be brought into the plane of projection and thus project the cut-off line in almost the same way as a classical slide projector.
- The whole headlamp can be moved. This solution is similar to the headlamp levelling system and can be used for projection and reflector systems.

A major drawback of the first solution is, that it is not obvious what happens to the discharge arc in the Xenon lamp if the lamp is accelerated. The third solution has the disadvantage that it involves moving a large mass. Thus the second design alternative turns out to be the most favourable.

In the next step the decision had to be made of how the shutter should be guided, and which kind of motion was the most appropriate for bringing it into the light beam. The shutter could undergo linear or rotational motions or a combination of both, and in each case there are three different possible axes of displacement or rotation. Fig. 5.32 shows some examples.

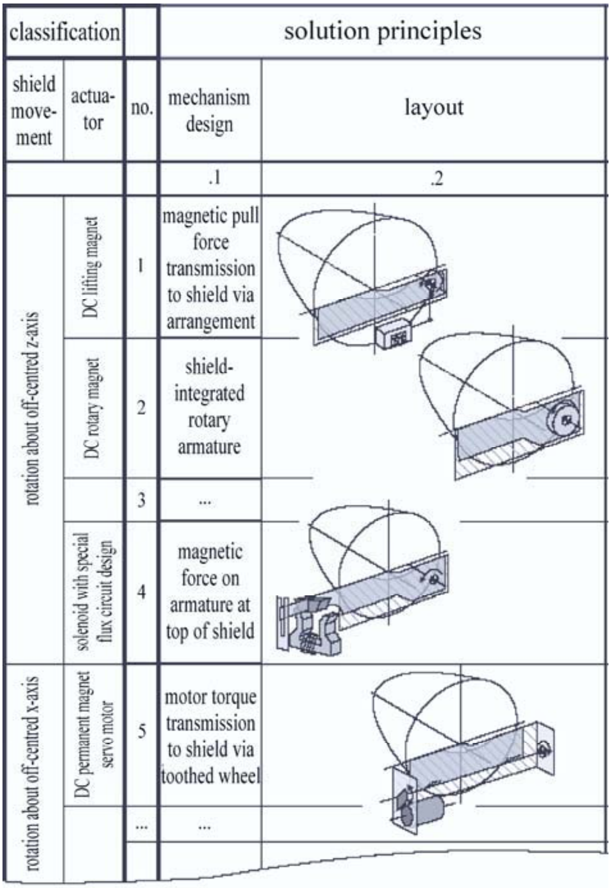


Fig. 5.33 Possible actuator concepts for the motion of the shutter (Börnchen, 2001)

Depending on the solution chosen for the guidance of the shutter's motion, several different actuator technologies can be used. The most widespread actuators are electromagnetic actuators (motors or voice coil actuators). But there are also piezoelectric actuators, shape memory alloys and other technologies that could be made use of. Some of these technologies allow highly integrated designs, where for example, the shutter itself might be a part of the magnetic circuit, while others are extremely cheap and simple and well-suited for mass production. In order to evaluate systematically the advantages and disadvantages of each individual solution, the actuators were characterised with respect to several criteria.

Fig. 5.33 shows a corresponding design catalogue, which formed the basis for the evaluation process. The main reason why, in the end the electromagnetic actuator dominated, was that these actuators are a proven technology. They are extremely cheap and robust enough for automotive applications.

The final design of the chosen solution was based on extensive simulations of the dynamic behaviour of the system. Fig. 5.33 shows a comparison between the results of a multi-body dynamics simulation of the system and experimental data obtained from a fully equipped prototype (Börnchen 2001).

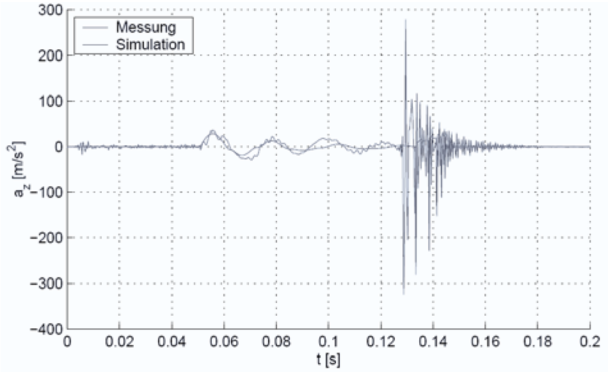


Fig. 5.34 Comparison of simulated and experimentally measured response during switching process (Börnchen 2001)

Summary and outlook

The Bi-Xenon projection system has become the present state-of-the-art. It allows the generation of two light distributions using only a single light source. With the introduction of adaptive front-lighting systems, it will no longer be sufficient to produce just two light distributions. The solution based on the moving shutter will become obsolete. The next generation of Xenon headlamps will still be projection systems, but use a rotating profile shaft instead of the shutter. A first example of such a system is the Variox module shown in Fig. 5.35.

Fig. 5.35 Variox module

Pixel light / DMD based headlamps

Fig. 5.36 shows a sketch of a headlamp that uses a digital micro-mirror device (DMD) to form the light distribution. Light is collimated and then projected onto the DMD. Those elements of the chip corresponding to areas of the light distribution which should be fully lit, remain in their neutral position, while those elements corresponding to areas of the light distribution which should be dark, are permanently switched to their off-position. Luminance intensities between fully lit and completely dark can be realised by pulse-width modulation of the elements.

Fig. 5.37 shows a typical DMD-chip. The tilt angle is typically in the order of 10° and the elements, which have a size of roughly 20 µm by 20 µm can be switched extremely fast at mirror transit times in the order of a few µs (Dudley et al 2003).

Headlamps based on DMD-chips work theoretically in the same way as a data or video projector. There is however, an important difference. Projectors are made to illuminate homogeneously a planar area that lies perpendicular to the direction of emitted light. In contrast, automotive headlamps should illuminate a long and narrow region of the traffic space in a rather inhomogeneous way. Most of the light should be concentrated at greater distances in the middle of the road. This leads to completely different optical designs for the video projector and a pixel light (Enders 2001), (Caustic et al 2003).

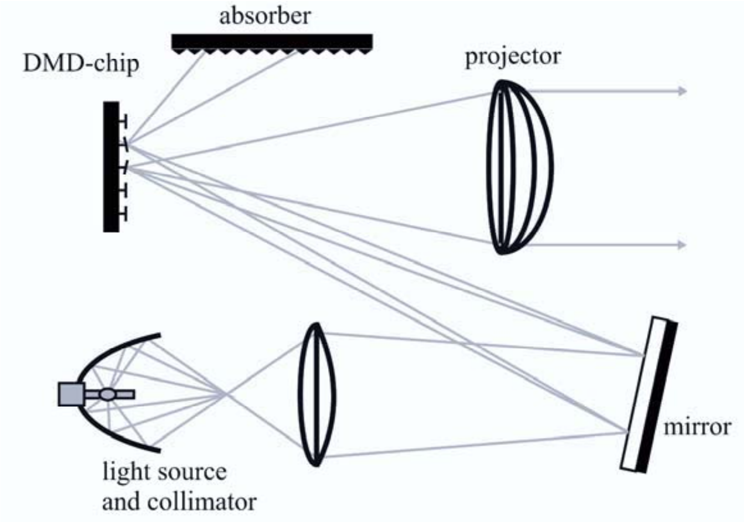


Fig. 5.36 Headlamp on the basis of a DMD chip.

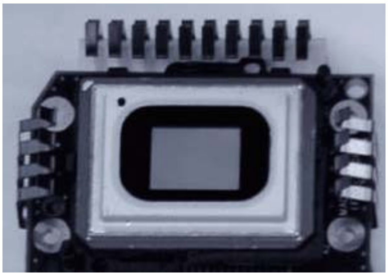


Fig. 5.37 DMD-chip

Scanner systems

Theoretically scanner systems can also be used in an automobile headlamp. The beam of light emitted from a laser diode or another suitable light source is deflected by two orthogonal movable mirrors. An alternative design comprising a single mirror that can be tilted on two axes is shown in Fig. 5.38.
By turning or tilting the mirrors, the light beam can be made to scan the area to be illuminated. By appropriate switching of the light source, arbitrary light distributions can be “written”- as long as the motion of the scanning mirrors is fast enough to prevent the eye resolving the individual

light pulses. The principle of this scanning headlamp is comparable to a laser TV system.

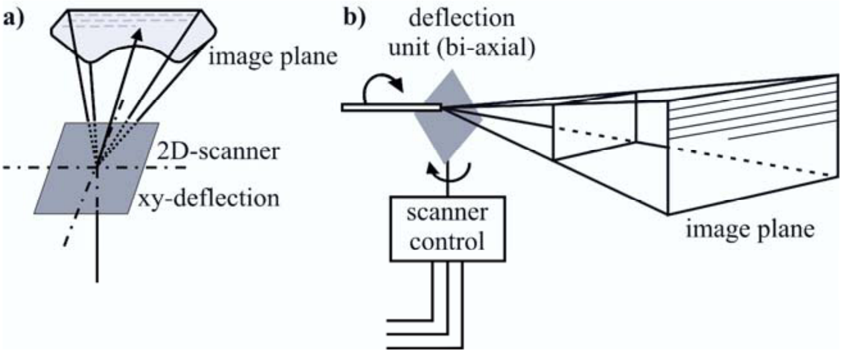


Fig. 5.38 Scanner system

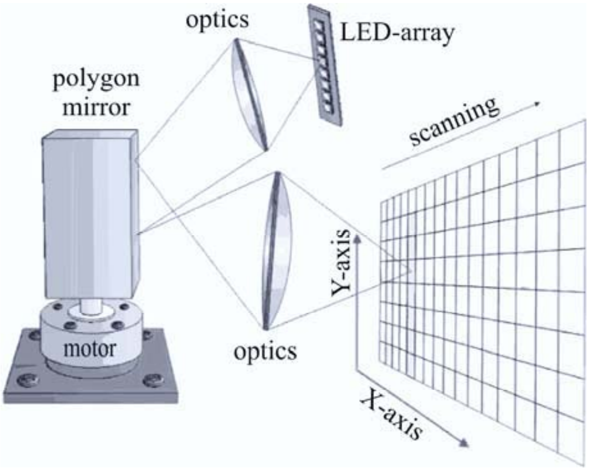


Fig. 5.39 Combination of LED array and rotating mirror

LED arrays

In contrast to pixel light and scanner systems, LED arrays are capable of creating a variety of different light distributions without using moving elements. Here the light emitted from a large number of light sources (LED chips) is superimposed. The LED chips are arranged in specific patterns. The optical system has to be designed in such a way that the desired light distributions can be generated by superimpositions of the light distributions generated by each individual LED. The intensity of the LEDs can be modulated, giving additional degrees of freedom.

Of course it is also possible to combine LED arrays and moving mirrors. An interesting solution is the combination of an LED array and a single rotating mirror, shown in Fig. 5.39.

5.4.3 Functional structures and functions of active lighting systems

Applying the generic "Sense – Think – Act" topology to active lighting systems, we obtain the functional structure of Fig. 5.40. The main function of the active lighting system to "illuminate the traffic space" is broken down into the sub-functions "recognise traffic situation", "calculate optimal light distribution" and "generate light distribution".

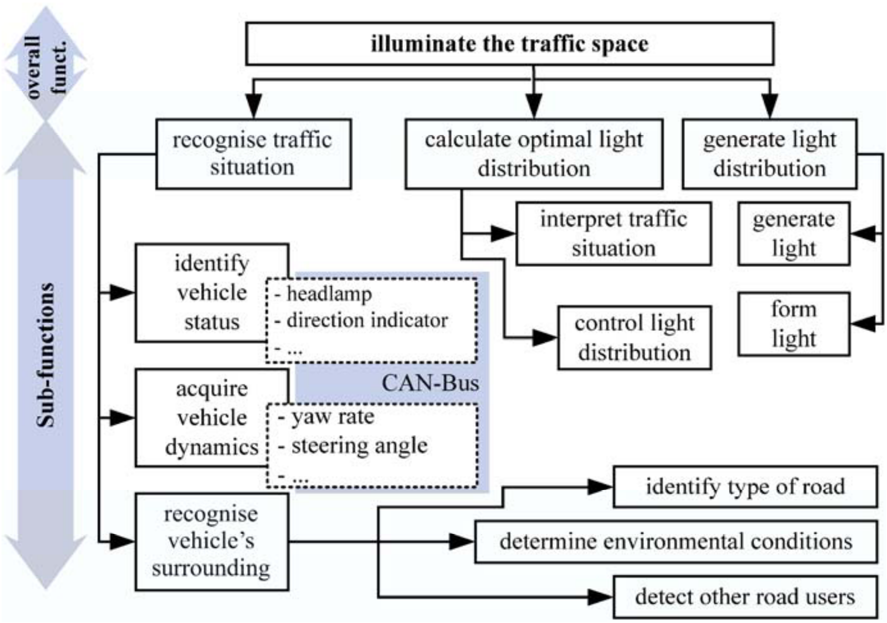


Fig. 5.40 Functional structure of an active lighting system (Roslak and Wallaschek 2004)

The main benefit of using the mechatronics approach is that most of the most important functions to be realised by the active lighting system can all now theoretically be reduced to a piece of computer software. This does not mean that sensors and actuators are less important, but due to the modular structuring, their selection and optimisation can be performed more conveniently on a local level. Depending on the task at hand, one must of course, still decide which sensors are most appropriate for a given task, and which headlamp concept will show the best performance. Nevertheless, the task of designing the system has obviously become less complex, compared to an unstructured 100% top down design approach.

We will discuss below some functions that can be realised using an active lighting system.

Marker light

The marker light function aims at illuminating objects outside the reach of the dipped beam distribution and/or to highlight those inside the light distribution. The goal is to draw the driver's attention as early as possible to potential danger spots and thus to extend the reaction time available to the driver.

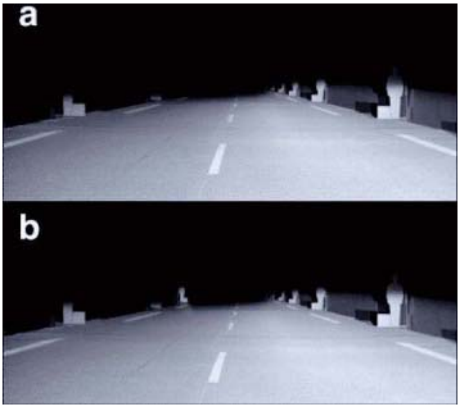


Fig. 5.41 Example of marker light. The pedestrian is outside the reach of the dipped beam. He is invisible in the upper photograph, which has been taken using the dipped beam distribution. He becomes visible if an additional marker light is used, as in the lower photograph. (Eichhorn et al 2005)

Fig. 5.41 shows an example of an object outside the dipped beam distribution that has been highlighted by marker light. If objects outside the reach of the dipped beam distribution are to be marked, the marker light function strongly depends on data from long range sensor systems. It is necessary to consider that the headlamp must be capable of producing a high intensity light spot, which can be freely positioned and which can follow the trajectory of the highlighted object, even at high relative velocities.

Glare-free main beam

In a certain sense the ‘glare-free main beam’ is the inverted function to a marker light. Marker light works on the basis of a dipped beam, but additionally and selectively highlighting objects in- or outside this light distribution. The ‘glare-free main beam’ works on the basis of a light distribution which provides excellent visibility, and selectively filters out those areas where glare for others would otherwise occur. Given the fact that the full main beam is little used in night-time travel, a ‘glare-free main beam’ would represent real progress towards improved safety.

The next spotlight is a case study on a ‘glare-free main beam’ system and on the sensors and sensor systems which were needed to realise it.

Spotlight

Vehicle surroundings - Sensing technologies for active lighting

Introduction

Over the past few years, several safety systems have been developed (such as ABS, ASP, ESP, etc.) to increase safety on roads. These systems use information about the dynamics of the vehicle. The next step will involve using information about the road and traffic situation in front of the vehicle to support the driver. The first assistance systems such as lane departure warning or blind spot detection have already been developed to warn drivers in hazardous situations.

Progress in surroundings-sensing technologies has allowed the development of efficient driver assistance systems. The interesting question is whether the same surroundings-sensors can also enable significant improvements in lighting technology.

Based on current headlamp systems, the adaptive front-lighting system (AFS) is about to be introduced. It is capable of producing a discrete set of pre-defined beam patterns, which are switched automatically in response to changing traffic and environmental conditions (vehicle speed, type of road, weather). Future headlamps will not only be able to generate variable assisting beam patterns, but also be able to generate a whole continuum of specific light distributions, using digital mirror devices in so-called "pixel-light", as described by (Enders 2001) and (Kauschke 2006). These novel headlamps can be used in combination with surroundings-sensing, thus allowing the presence of other road users to be taken into account. They will improve visibility for the driver and minimise glare to other road users at the same time. Cornerstones for the development of such active lighting systems are sensors for sensing the traffic around the vehicle.

Table 5.1: Characteristics of surroundings sensors for active lighting applications

required sensor-property	77 GHz Radar	Lidar	24 GHz Radar	Stereo Vision
range	-	-	-	●
range resolution	●	●	●	○
opening angle	-	-	○	●
angular resolution	-	○	-	●
velocity range	●	●	●	●
velocity resolution	●	●	●	○
length of measurement cycle	●	●	●	○
weather independency	●	○	●	-
self-assessment	-	○	-	●
detection robustness (classification capability)	○	○	○	●

● *good;* ○ *fair; - poor*

Surroundings-sensing technologies

In the automotive industry different sensing technologies have been adopted to explore the surrounding road environment. The main task is to detect other road users, or to recognise hazardous situations. Detection algorithms are used to extract information such as obstacle type, distance, speed or orientation relative to the vehicle. The sensors that are available today vary in performance, robustness and operative range. Microwave radars, laser radars and artificial vision devices seem to be the most promising technologies. All these individual sensors deliver specific information about the detected objects. They can be used independently or can be used in data fusion, which means that several sensor systems are made to work together, complementing each other. The choice of the particular sensor technology depends on the specific application requirements.

The list of requirements for surroundings-sensing technologies is long. Some of the most important general demands are listed in Table 5.1, which also includes a qualitative judgement about the relative performance of the most widely used surroundings-sensing technologies with respect to particular demands.

An important criterion for the choice of the sensor technology is of course, its performance in detecting all relevant objects within the traffic around the vehicle. A large range in combination with a wide opening angle is probably the most important criterion for sensors being used for object detection in an active lighting system. Table 5.1 suggests that today stereo vision is probably the most attractive surroundings-sensing technology for active lighting.

Microwave radar

Several radar systems are currently under development for various automotive applications. Radar allows the estimation of target velocities and distances in both the lateral and longitudinal direction with high accuracy, and can also be used in situations where multiple objects have to be detected.

Microwave radar sensors measure time of flight, power and the Doppler frequency shift of electromagnetic waves transmitted from the sensor and reflected back from the obstacle. The time of flight is evaluated to obtain the distance and the Doppler frequency for the velocity of an obstacle.

The use of automotive radar sensors for obstacle detection has the advantage that their recognition performance is almost unaffected by bad weather, poor visibility or harsh environments, such as snow or ice. They can be mounted invisibly behind non-conductive materials, so that the vehicle design is not disturbed in any way.

Two microwave sensor technologies have been specifically developed for the automotive industry. The 77 GHz technology allows for covering an observation area in front of the vehicle up to a maximum range of about 200 m, at a narrow opening of about 10°. The Near Distance Sensors (NDS), which are based on 24 GHz technology, cover a wide azimuthal field of view, but only within a very short range of 50 m.

The first application for Far Distance Radar Sensor (FDS) based on 77 GHz technology was the Adaptive Cruise Control (ACC) function. The use of the radar sensor in the ACC system allows the determination of the distance of objects ahead of the vehicle.

The 24 GHz radar operates in pulsed mode using ultra short pulses that make it possible to achieve a high range resolution even for very short distances.

Lidar

An alternative to Far Distance Radar Sensors is an infrared sensor also known under the name LIDAR (Light Detection and Ranging). Its operating principle is based on laser time of flight measurement. A short infrared light pulse with a high peak pulse power is generated by a laser diode and transmitted in the direction of the object. The system calculates the distance to the object from the run time of the reflected beam. To achieve high lateral resolution and a wide horizontal opening angle, the LIDAR sensor has been designed as a multi-channel device.

The optical nature of the signal generated by the LIDAR sensor causes significant susceptibility of its sensing capabilities to atmospheric influences such as rain or fog. In addition, being an optical system, the LIDAR can only be installed behind transparent components, for example behind windscreens or in headlamps.

Artificial vision

Various types of video-based sensing systems have been developed for sensing stationary and moving obstacles. These sensors provide a high spatial resolution, both horizontally and vertically. In comparison to other technologies, the video-based sensor systems allow the collection of more information about recognised objects. For example they can also detect the shape, velocity and precise spatial location of an object.

Cameras used in video-based sensor systems must have a high resolution and a high dynamic range to enable operation in diverse lighting conditions. Powerful image-processing algorithms and fast processors are required if the systems are made to operate in real time.

Stereo vision allows the detection and spatial location of obstacles within a distance of up to more than 400m. The position of the object is calculated by triangulation of matched image features in one left and one right camera image.

Video sensors can provide a wide spectrum of information on the traffic situation that is “invisible” to other sensors. However two performance measures still need to be improved: 1) the dynamic range of the camera sensor needs to be increased, since the headlamps of other vehicles can blind the sensors, and 2) the amount of processing power required for video images must be reduced.

Case study: glare-free main beam

Glare impairs visual perception. Glare is a problem that not only affects oncoming traffic, but also vehicles moving in the same direction. Light from following vehicles may dazzle the driver if it is reflected in the mirrors. In order to completely eliminate glare it would be sufficient if those parts of the light distribution that affect other traffic participants were suppressed in the headlamp beam. Roslak (2005) investigated an active lighting system where information sampled from surroundings-sensing was used to control a headlamp based on a digital mirror device. Light was only emitted in those directions where it could not produce glare.

The idea was to use the main beam permanently and shade those parts of the light distribution that would dazzle others. Fig. 5.42 shows a basic representation of the individual areas of light distributions according to ECE regulations. The area directly in front of the vehicle is illuminated by the base beam pattern that is similar to today's dipped beam. The active system only addresses the area above the horizontal cut-off line, where the light distribution is modulated locally between no light at all and the full intensity of the main beam. An analysis of traffic space geometry and fixation spots showed that the active area can be limited to 4° above the horizontal line.

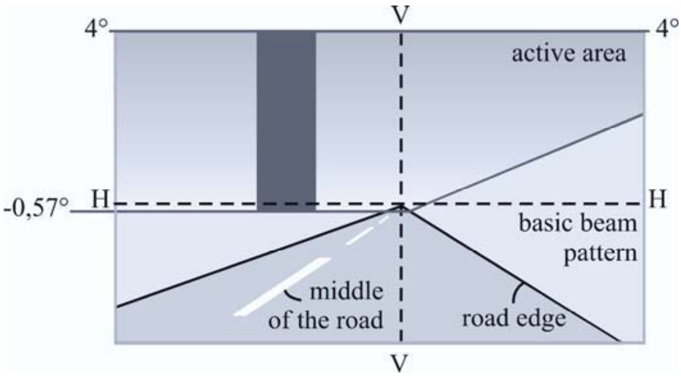


Fig. 5.42 Principle representation of individual sections of the beam pattern in a measuring screen according to ECE No. 8

The glare-free main beam was evaluated from both physiological and psychological points of views. A significant point was to determine the amount of glare at the eyes of oncoming drivers. The determination of glare illuminance was carried out for three different beam patterns produced by the active headlamps. The illuminance was measured for the dipped beam and main beam, as well as for the glare-free main beam. The glare values corresponding to the two conventional beam patterns form the reference values. Fig.5.43 shows the illuminance values in the eyes of an oncoming driver recorded for all three beam patterns. The results show that the illumination created by the glare-free main beam is not above the allowed illuminance for dipped beam, as long as the distance is within the detection range of the sensor.

The subjective judgement of the glare-free high beam by non-expert test subjects was also recorded during the tests. Night-time drives were carried out with dipped beam, main beam and glare-free main beam under the same traffic conditions. The drivers were able to evaluate the light both from the perspective of the driver of the vehicle fitted with the glare-free main beam, and from the perspective of the driver of the oncoming vehicle. This allowed the subjective evaluation of both the benefits of the light system and its effects on other road users. The result of the survey confirmed the proper operation of the glare-free main beam system.

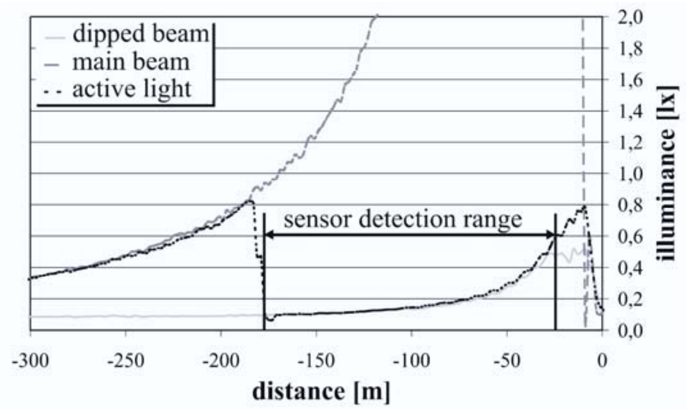


Fig.5.43 Glare illuminance in the eyes of an oncoming driver for dipped beam, main beam and active light (glare-free main beam)

Outlook

A critical point in surroundings-sensing is still their insufficient range of detection. Presently, artificial vision seems to be the only technology that allows for enough detection range. Thus progress in this field will also significantly increase the potential of this application.

Active lighting systems based on surroundings-sensors make a large number of new lighting functions available. These have huge potential to make driving at night safer and more comfortable.

Cooperative lighting

Another scenario of active lighting is cooperative lighting. The light distributions of all vehicles and road or tunnel infrastructure involved in a traffic situation are superimposed with the aim of providing optimal conditions for the visual perception of all persons involved.

Present day lighting distributions have been optimised for traffic situations where only a few vehicles are involved. In situations where many vehicles are involved, such as inner city traffic or dense traffic on the motorway neither the dipped beam nor any other light distribution are optimal. The idea of cooperative or ‘platoon’ lighting is about using specific light distributions, which take into account the presence or other vehicles.

Cooperative lighting in its most general sense, goes far beyond the idea of platoon lighting, by further adapting the individual light distributions to the actual situation e.g. the relative positions and orientations of all vehicles involved For this lighting function, a mathematical formulation, whose essentials are summarised in Fig. 5.44, has been given (Roslak and Wallaschek 2004). Let us start with the acceptable illuminance in front of the eyes of the persons involved in a specific traffic situation, assuming that glare is caused only by direct light i.e. reflections can be neglected for simplicity. If the position and orientation of all persons and all light sources involved is known, the acceptable luminous intensity of each headlamp can be calculated as a function of the emission angles. These limiting values are then formulated as restrictions for an optimisation problem. In the next step the light distributions of all headlights are superimposed, to give the resulting light distribution as a function of the individual light distribution of the individual headlights. The last step is the formulation of a restricted optimisation problem. Here for example, the aim could be to maximise the minimum of the illuminance of the resulting light distribution. Of course the same approach could be used to include primary and multiple reflections, but we will not go into the details here.

Collective lighting could also mean that road lighting and vehicle lighting are controlled simultaneously. For example tunnel lighting could be switched on when vehicles are in or near the tunnel, and turned off in the absence of vehicles. But when combining road lighting and vehicle lighting, it must be kept in mind that vehicle lighting is designed to help the driver detect objects by producing luminance contrasts with respect to the background, while road lighting is designed to light the road surface uniformly. Under certain conditions, the combination of both types of lighting can even reduce visibility. Any control algorithm for cooperative road and vehicle lighting must take this into account.

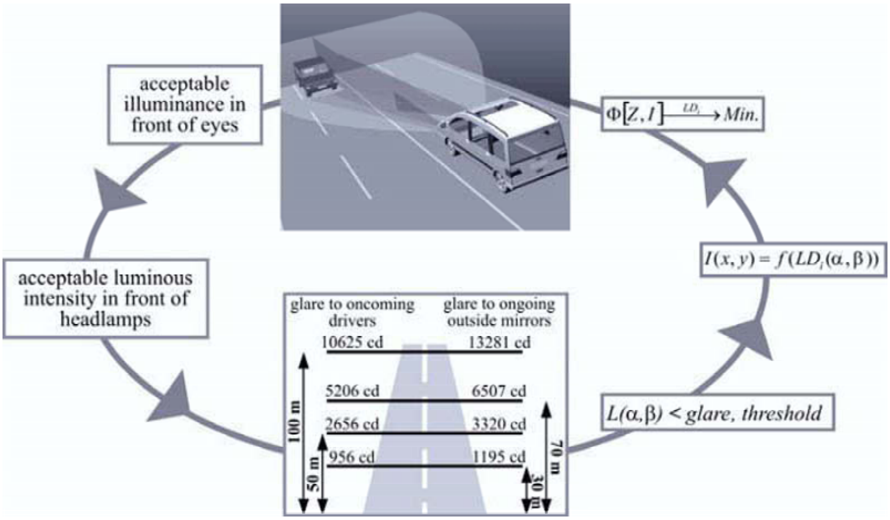


Fig. 5.44 Mathematical framework for collective illumination

The proper choice of the quality function is an open question in this and in other mathematical optimisation problems related to automotive lighting. This will be addressed in the next spotlight.

Spotlight

Quality of automotive headlamp beam patterns

Introduction

We need a rating scheme in order to decide what is a good headlamp and what is not. One way to get subjective rating is simply to ask the drivers which properties a headlamp beam pattern should have in order to ensure safe and comfortable driving. We can expect the answer to be along the lines of “Sufficient brightness in front of the vehicle, sufficient width, good uniformity, high recognition distance with as little glare as possible”. Indeed brightness, visual range, width of illumination, homogeneity and glare are internationally accepted quality criteria for headlamps. Rather than simply applying a subjective rating scheme, it would be helpful to use photometric measurement values to arrive at an objective rating scheme.

Photometric quantities

In the field of lighting there are four basic photometric quantities: luminous flux, luminous intensity, illuminance and luminance. It would be optimal if we could define photometric values which are directly related to our perception of brightness, visual range, width of illumination and homogeneity. Unfortunately, conventional techniques do not allow us to perform such measurements directly.

Theoretically, all photometers measure illuminance. As it is possible to calibrate an illuminance meter with respect to luminance, there are both illuminance meters and luminance meters. Both devices are used routinely for the measurement of photometric quantities.

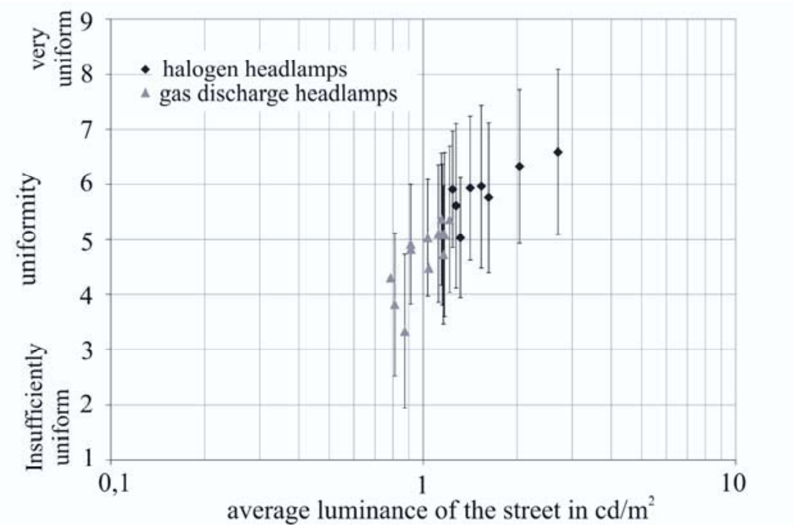


Fig. 5.45 Evaluation of brightness (1 = too dark; 9 = too bright) as a function of the average luminance of the road

Brightness

All visual functions depend on brightness. The brighter the illuminance of a street scene at night, the better the visual performance. A photometric quantity that is related to brightness is average luminance. As the luminance of a street also depends on the luminance factor of the street, a fitting standard value must be used in testing facilities. Figure 1 shows the judgement of brightness of the street depending on the luminance of the street, for a luminance factor of 0.07 cd/m²/lx and an evaluation field of 10m by 100 m in front of the vehicle.

The following general results hold for automotive lighting (Völker 2006):

- The observed brightness of the street increases with higher luminance
- Automotive lighting should provide a minimum average luminance of 1 cd/m² for acceptable road illumination
- Neither the beam pattern, the light colour nor uniformity have significant influence on the subjective evaluation of brightness

Other investigations, e.g. (Dahlem 2000) obtain similar results. Thus, the following five-star rating of brightness can be suggested:

Table 5.2 Rating of brightness

L in cd/m²	L < 0.7	0.7 < L < 0.9	0.9 < L < 1.3	1.3 < L < 1.7	L > 1.7
Rating	*	**	***	****	*****
	very poor	poor	adequate	good	very good

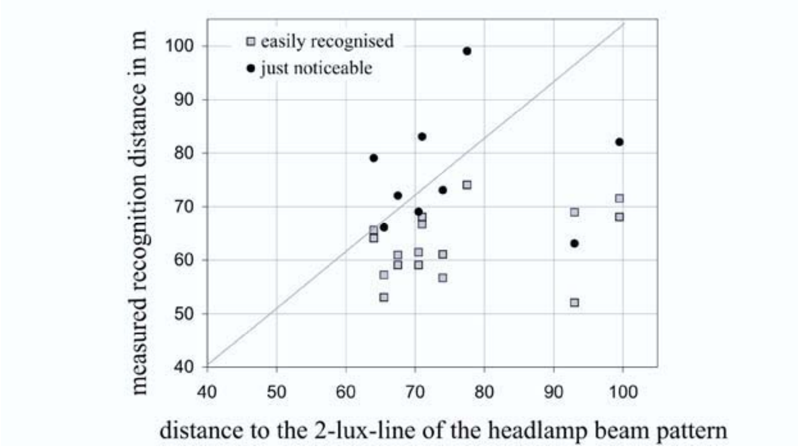


Fig. 5.46 Recognition distance of a grey panel (0.3 m by 0.3 m, ρ = 7.2%) from the 2-lux-line comparable with the real recognition distance

Recognition distance

Everyone agrees that recognition distance is a very important factor for safety. Lighting engineers have been working on the calculation of recognition distance for many years. It has been emphasised again and again that illuminance is not a suitable photometric value for calculating the recognition distance. To illustrate the point Fig. 5.46 shows the correlation between the experimentally determined recognition distance and the distance of the 2-lux-line of the headlamp beam pattern.

The model of Kokoschka (Kokoschka 2000) uses luminance values to calculate threshold contrasts. This allows estimation of the recognition distance for a standard object under static conditions. Fig. 5.47 presents the correlation between the calculated and the measured recognition distance.

Although it is not yet possible to make statements about recognition distances in real road traffic using this data, it is now possible repeatably to compare different headlamps with respect to recognition distance. The following grading scale is suggested.

Table 5.3 Rating of recognition distance s of a target 300 mm x 300 mm on the driver's side of the road, centre, rho = 4.6%

s in m	< 55	55 < s < 60	60 < s < 65	65 < s < 70	> 70
Rating	*	**	***	****	*****

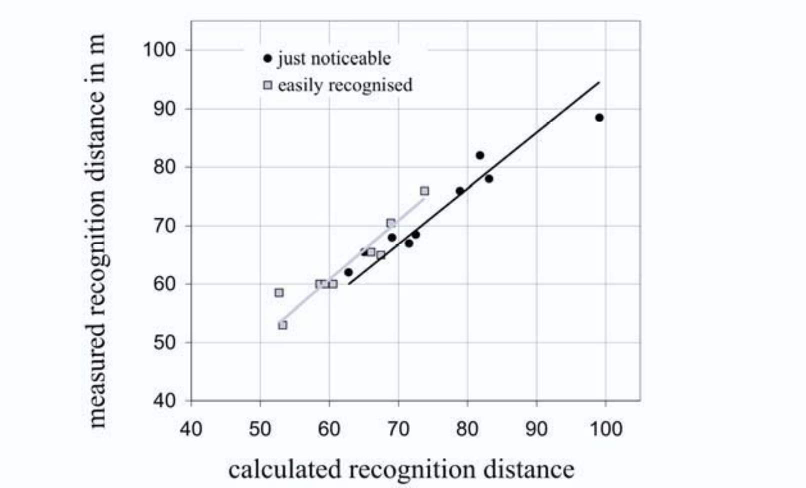


Fig. 5.47 Correlation between the calculated recognition distance and the measured recognition distance

Uniformity

The quality criteria "Uniformity of the beam pattern" plays an important role for visual comfort i.e. reduced stress whilst driving. Various authors, who have investigated homogeneity, concluded that light and dark stripes tend to cause the driver continually to shift glances. In addition, dark spots can either wrongly suggest imperfections in the road surface or conceal holes in the road, thus leading to false reactions by the driver (Fig. 5.48)

(Hamm and Lampen 1999; Wang et al 1995). From the analysis of the time required for adaptive processes, Lindner deduced that only minor variations in luminance could be tolerated within the driver's field of vision. This leads to the requirement of high local uniformity in the beam pattern of vehicle headlamps.

Kleinkes (Kleinkes 2003) developed a so-called ‘quality figure G’, which can be used as a photometric quantity in combination with the luminance gradient. The uniformity can then be described by means of the partial derivatives of the luminance in horizontal and vertical direction. A result of the gradient analysis using partial derivatives is presented in Fig. 5.48. The gradients are shown as arrows, representing the normals of the indicated contour lines of a luminance image.

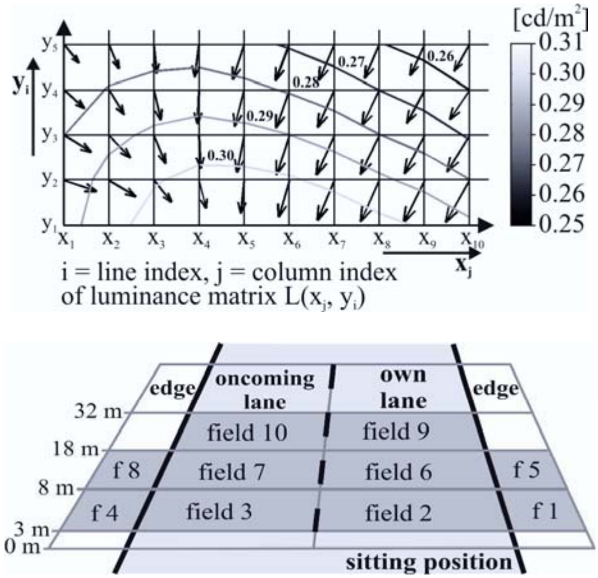


Fig. 5.48 Gradients in a distribution of luminance from 10 by 5 units (top), 10 evaluated fields (bottom)

Fig. 5.49 shows the correlation between the calculated uniformity G and the subjective evaluation made by the test subjects. Using the ‘quality figure G’, the following scale is suggested to rate homogeneity:

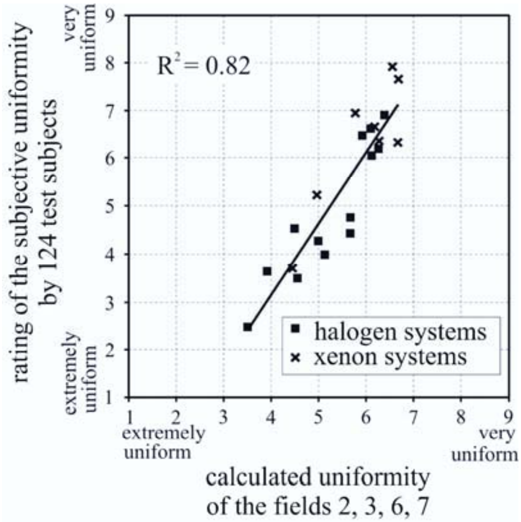


Fig. 5.49 Comparison of the calculated uniformity G with the subjective evaluations made by the test subjects

Table 5.4 Rating of uniformity

Uniformity G	< 3	3 < G < 4.5	4.5 < G < 5.5	5.5 < G < 7	G > 7
Rating	*	**	***	****	*****

Glare for oncoming drivers

Glare leads to a decrease in visual performance and causes discomfort. We know that with current headlamps, glare can not be completely eliminated without jeopardising recognition distances. Glare is the result of a compromise that we can improve only by means of optimisation.

The illuminance at the observer’s eye can be used as the photometric value directly relating to disability glare. Above the cut-off-line, an illuminance level of 0.7 lx per headlamp only, measured at 25 m distance is allowed in the ECE regulation. The value of 0.7 lx per headlamp is internationally regarded as the optimum between recognition distance and glare on single carriageway roads.

For some years additional photometric values were discussed to describe glare, for instance the average luminance or the area of headlamp and the spectral distribution. Raphael and Völker (Völker 2005; Raphael 2004) investigated the influence of illuminance on discomfort and disability glare.

The results can be summarised as follows:

- The illuminance is the main single factor for disability and discomfort glare
- The luminance does not influence disability glare as long as the illuminance is less than 1 lx. In order to guarantee this under most driving conditions, a dynamic levelling system is recommended for all vehicles.
- The luminance of the headlamp has an influence on discomfort glare.

To improve the safety and the comfort of drivers, additional limits of luminance to the current limits for the illuminance should be used. The following table contains suggestion for the rating of glare:

Table 5.5 Evaluation of glare

Average luminance L_m in kcd/m²	$L_m > 40$	$30 < L_m < 40$	$20 < L_m < 30$	$10 < L_m < 20$	$L_m < 10$
Evaluation	*	**	***	****	*****

5.4.4 Active signal lights

The conspicuity of signal lights depends on a good contrast to their environment with respect to both luminance and colour. In choosing the proper luminance for a signal light, a compromise must be found between “sufficient luminance for contrast at high ambient illumination” and “avoidance of high luminance causing glare”. In contrast to classical signal lights where the luminance is fixed at a constant value, adaptive signal lights can change the luminance of the signal, depending on the ambient illuminance (day, night) and weather conditions (fog, rain).

Active signal lights go one step further. They not only change luminance depending on environmental conditions, but give additional information by changing their shape, or by flashing or blinking. In this way they can for example, not only indicate that the vehicle brake is applied, but also indicate the braking acceleration to the following traffic. Using LED technology it is an easy task to make the apparent area of the display proportional to the braking acceleration, or to make the brake lights flash when the braking acceleration is above a certain threshold.

Using car to car communication, an active signal light could even signalise an accident on the road by automatically flashing the brake lights of all vehicles approaching the location of the accident. Using car to infrastructure communication, road lighting might also be employed for this type of information flow.

Those with experience of German motorways may know the following tricky situation: the difficulty of judging whether a driver in front of you will stay in his lane or overtake a vehicle in front of him, when his vehicle is considerably slower than your vehicle, but slightly faster than the one in front of him. In such a situation, car to car communication could be used to establish a connection between the two drivers. The driver of the vehicle in front of you could be warned that there is another car behind approaching at high relative velocity. If he is in the right mood, he could then express that he has recognised the situation and the approaching vehicle can pass safely. Alternatively he might decide to overtake nonetheless, sending a signal to the driver of the approaching car, who could then start to decelerate early enough.

The next spotlight will be on emergency lighting. As many new lighting functions, including active signal lights, are first tested in virtual reality environments, another spotlight will then introduce some background on this technology and its tools.

Spotlight

Emergency vehicle lighting

Identifying emergency vehicles

Emergencies happen. Cars break down. Crashes occur. These events bring out emergency vehicles. Emergency vehicles such as ambulances, police cars, fire engines and breakdown recovery vehicles, have additional lighting differentiating them from other vehicles. This additional lighting usually consists of a number of flashing point sources, different colours being used to indicate the function of the vehicle. Unfortunately, different colours are used for the same function in different countries.

Functions of emergency vehicle lighting

Flashing point sources that are visible from all directions are undoubtedly effective in enhancing the conspicuity of the emergency vehicle, but if it is the only lighting available to an approaching driver, confusion may occur. This is because judgements of position and movement are more difficult under strobe lighting than under stable lighting (Croft 1971). Anyone who has approached the scene of an accident attended by three police cars, a fire engine and an ambulance, all with multiple flashing lights of different colours operating on different phases, will recognise the difficulty. The additional lighting on emergency vehicles has three purposes: to identify them as emergency vehicles, to make their presence obvious and to ensure that their sometimes unusual manoeuvres can be easily seen. What is needed is a system of additional lighting that can fulfil all three objectives.

A rational solution

A rational solution to this problem has four parts.

- Retain the colour coding used for identification
- Limit the number of identification lights to two, visible from all directions and operating on opposing phases
- Replace the flashing identification lights with pulsing identification lights
- Provide pairs of extended strips of light marking the edges of the vehicle (Fig. 5.50)

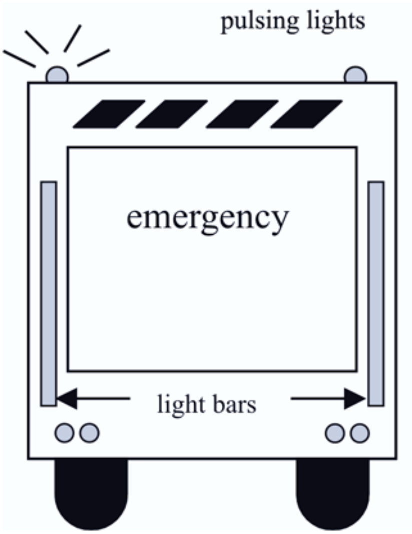


Fig. 5.50 Emergency vehicle with light bars and pulsing lights

Each element of this solution can be justified as follows:

The colour coding is a learned association. It takes time to develop such associations, and as they are well established, there seems little point in changing the colours unless there is a need for uniformity over a larger area of the traffic system e.g. the whole European Union.

Limiting the identification lights to two is unlikely to reduce conspicuity, provided they are both visible from all directions. Further, by making them operate on opposite phases, conspicuity will be enhanced. This is because in addition to the fluctuation in light output of the individual lights, there will be an illusion of movement between the two lights (Palmer 2002). Peripheral vision is particularly sensitive to movement.

The difference between a pulsing light and a flashing light is the percentage modulation of the light output fluctuation. A flashing light has 100% modulation. A pulsing light has a lower percentage modulation. Therefore, a pulsing light provides some steady light output, making it easier to identify position and movement. As the percentage modulation is reduced from 100%, it is believed that initially, there will be little change in conspicuity. But at some point, conspicuity will diminish rapidly. This suggests that it should be possible to reduce percentage modulation without sacrificing conspicuity. Exactly what the percentage modulation should be to strike an appropriate balance between conspicuity and visibility remains to be determined.

Pairs of bright, stable, large area lights have been shown to be more effective in enabling drivers to estimate movement and relative speed than either small area marking lights or a single large light (Mortimer 1969; Bullough et al 2001).

Spotlight

Virtual reality tools for headlamp design

Introduction

Modern automotive headlamps must meet numerous requirements: technical restrictions, legal obligations, design needs or customer demands, to name but a few. Especially the various different technical requirements, have led to the complex lighting characteristics of modern headlamps. These lighting characteristics of modern headlamps are defined by a two-dimensional distribution of the luminous intensity (see Fig. 3.2 schematic view of light distribution, chapter Automotive Lighting – State-of-the-Art). This distribution basically defines how much luminous intensity leaves the headlamp under a certain angle, in a horizontal and vertical direction relative to the direction the headlamp is pointing. Values for the luminous intensity show a great variation, leading to a very high dynamic range of 0 – 100.000 cd for a typical main beam headlamp. In combination with the light intensity fall-off, these different luminous intensities and their distribution result in a complex light silhouette of the headlamp on the road in front of the car.

Design and evaluation of such complex lighting characteristics require numerous test drives in a test vehicle at night. But this is time-consuming and expensive.

Virtual Reality (VR) tools facilitate the design and evaluation process of automotive headlamps by providing interactive close-to-reality simulations of test drives at night. Such tools are capable of visualising complex lighting conditions during a simulated night drive in real time, and respond immediately to user interaction using sophisticated display and simulation hardware. Thus:

- the user feels immersed in the VR-simulation i.e. the user gets the impression of conducting a real night drive
- the user can interact intuitively with the simulated world i.e. drive the simulated vehicle along a test track and see how the headlamps illuminate the scenery
- the user can easily try out different testing scenarios, which in reality would take a lot of time to perform e.g. change weather conditions, switch between different headlamp models or test tracks.

History

Originating from the field of flight simulation, applications of VR started to migrate into the field of driving simulation in the 1960s and 1970s. Since then most applications of driving simulation focus on simulating vehicle dynamics and the process of driving. VR-based driving simulation applications are used in the automotive industry to support design and development of suspension systems, to improve dynamic properties of a vehicle, or to simulate advanced safety systems like Anti-Lock Braking System (ABS) or Electronic Stability Programme (ESP), to name but a few. In most cases the optimisation of the system behaviour according to the driver's needs is the focus of the investigations. Other applications deal with driver safety and training e.g. the driving simulator at BMW or the National Advanced Driving Simulator (NADS) (see Fig. 5.51) at the University of Iowa.

Fig. 5.51 NADS - High-end driving simulator with 360°-projection dome and hexapod on top of a 2D linear motion system (left) and high frequency actuators driving the vehicle chassis inside the dome (right). (Source: NADS, University of Iowa)

With the growing performance in simulation hardware, especially in 3D graphics hardware, more and more complex simulation models and visualisation effects can be realised cost-effectively. Special night drive simulators for example, focus on simulating the illumination of the road at night, thrown in front by the vehicle's headlamps, during a virtual test drive.

Application

This section shows some examples of VR-applications for the development of headlamps. These applications can be found mainly in the automotive industry and its suppliers.

Car manufacturers for example Renault, use VR-based night drive simulators (Lecocq et al 1999), see Fig. 5.52. Their applications focus more on a generalised representation of the car's lighting to support headlamp validation, driver safety or training tasks, as well as presenting the complete car with all its technical features. Simulators in this area support more general functions of driving simulation, e.g. driving dynamics or the representation of the car itself, and have in general no special application focus.

Fig. 5.52 Renault's driving simulator: simulation of glare from oncoming traffic (left), tail lights (centre), and headlamps (right) during a simulated night drive (Source: OKTAL SA, France)

Fig. 5.53 Hella's night drive simulator 'Light Driver' in the L-LAB

Headlamp manufacturers for example Hella, use VR-based night drive simulators with the special aim of presenting and evaluating the lighting properties of new headlamp prototypes. These systems are focussed on a very detailed visualisation of the headlamps' lighting characteristics to support the design engineers in optimising the headlamps' lighting properties (see Fig. 5.53). Such simulator systems have to be able to present the complex lighting characteristics in high detail and at high speed, to support the evaluation and the design of the headlamp prototypes.

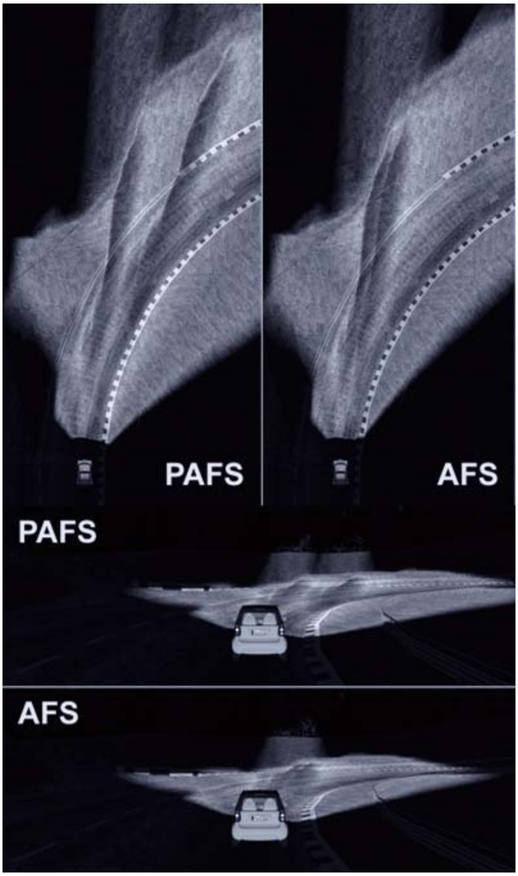


Fig. 5.54 Simulating Visteon's P-AFS lighting system with the *'Virtual Night Drive'*-simulator: Visualisation of bending behaviour with predictive and conventional AFS from bird's eye view (top) and a following car (bottom)

More advanced lighting modules e.g. Predictive Advanced Front Lighting Systems (P-AFS) (Ibrahim, Schmidt, Klein 2005), or levelling lights, require sophisticated functional simulations within the VR-based night drive simulation (Berssenbrügge et al 2003). In addition to visualising all lighting characteristics in high detail, the automatic bending behaviour of these systems has to be simulated as well. To achieve this, the control algorithms within the electronic control unit (ECU) of such a lighting system have to be connected to the simulator. This allows including the ECU's bending action of the headlamp according to the course the user drives along the virtual test track (see Fig. 5.54).

Simulating such a dynamic lighting system within a night drive simulation allows easy and quick testing of different parameter sets that control the bending algorithm of the P-AFS system. This facilitates the evaluation of a dynamic lighting system, leading to a clear reduction in the number of required real test drives at night and thus, leads to significant savings in time and costs.

Applications of night drive systems in academia mostly focus on investigating the driver's behaviour under different lighting conditions during a simulated night drive. The driver's viewing direction is analysed during a test drive in the simulator using an eye-tracking system (Locher et al 2005) (see Fig. 5.55). Moreover, additional physiological signals e.g. the driver's heart rate and blood pressure are monitored. Simulator systems in this application area are required to support functions for analysing the driver's behaviour according to the measured physiological signals during the simulated test drive.

Fig. 5.55 L-LAB-set-up of the virtual night drive-simulator (left) and examination of driver behaviour using eye-tracking (right)

Examining driver behaviour is necessary in order to be able to evaluate the quality of different lighting systems from the user's point of view. Typical applications examine the following topics for a representative number of users:

- How does the user's driving behaviour in the simulator differ from driving in a real vehicle?
- How much time is required to recognise obstacles on the roadway? and how long does it take to react in that hazardous situation?
- At what maximum range can obstacles be detected when using specific headlamps?
- How does the driver react when sudden glare from oncoming traffic occurs?

Outlook

VR-based applications in general, and especially in the field of automotive headlamp design, are driven mainly by the rapid development of new graphics processing units (GPU). Each new generation of graphics hardware currently doubles its performance about every 6 months. This even outperforms the so-called Moore's Law that predicts the performance growth of central processing units (CPU). These show a duplication in computing performance only every 18 months.

As the visualisation power of modern graphics hardware increases at breath-taking speed, and meanwhile easily outperforms the development of CPUs, dramatic improvements in the complexity and fidelity of graphics can be expected in the near future.

Every generation of new graphics systems supports more advanced visualisation effects and ever-increasingly complex simulation models. Thus new technological solutions facilitate new applications of VR-technology that were almost impossible for the previous generation of graphics systems to handle.

In addition to the performance growth, current GPUs base heavily on the shader technology. This new technology makes modern GPUs freely programmable and facilitates special application-specific visualisation techniques. It can be expected that the shader technology will revolutionise graphics capabilities even more than hardware-based fixed-function graphics pipelines did in the 1980s.

In the field of automotive headlamp design, several current innovative approaches for visualising illumination effects benefit from the rapid development of graphics systems:

- Advanced surface reflection models and custom-made visualisation effects can be computed in real time on a per-pixel basis, leading to high-quality results in visualisation for VR-based applications.
- High dynamic range data that typically describes the nature of a light distribution of modern automotive headlamps can be processed in real time and with high precision using the shader technology. New applications arise along with emerging new display systems, which provide very high contrast and brightness features to support the display of high dynamic range data.
- Online ray tracing aims to simulate lighting, based on computing individual light rays along with their reflection and refraction at lit surfaces. Using these approaches, significant improvements in detail and quality for visualisation can be expected.

5.5 Adding additional channels of perception

Let us go back to the system structure in Fig. 5.11. It shows a system that makes use of additional channels of perception e.g. a display. The information presented in this way typically refers to objects in the traffic space, which cannot be perceived or are difficult to perceive by the driver's eyes. Here are some technical systems serving the purpose of providing additional channels:

- Rear view camera: using a video camera and a display it is possible to survey the rear of the car, something which is nigh impossible from the driver's position. While this system might seem unnecessary for small cars, it is a very important safety feature for large vehicles like buses or trucks, especially for truck-trailer configurations, where the camera could be installed at the end of the trailer.
- Night vision system: the operational principles of night vision systems have already been explained in a previous section. However the information gathered by a night vision system can be used not only as input to an active lighting system. It could simply be displayed to the driver on a screen.
- Blind spot warning: side mirrors have a so-called blind spot, with the consequence that vehicles approaching from behind cannot be seen when they are outside the reach of the mirror images of the driver's eyes. A camera mounted in the side mirror or at any other suitable location or any other surround-sensing system, could be used to identify objects in the blind spot and warn the driver about their presence in certain situations.
- Travel pilot: the use of satellite navigation in combination with digital maps has become almost everyday technology. In a certain sense the travel pilot can also be considered an additional channel of information, bringing remote information to the attention of the driver. He is informed about the route, about traffic jams and weather conditions ahead and many other things that are beyond his immediate present environment.

A fundamental issue in adding further channels of perception is how to bring the additional information to the attention of the driver. Travel pilots use displays and/or speech. The blind spot warning might use an acoustic signal or vibrations of the steering wheel. Night vision and rear-view cameras need a display. But how does the driver interact with these systems? Will he accept them and do they disturb him rather than support him? How should the displays be designed? Which colours should be used for the display? Where should the displays be located? The optimal design of the man-machine interface is clearly one of the main challenges. It will be addressed in more detail in the next spotlight.

Spotlight

Humanocentric design of driver assistance systems

Driver assistance systems and innovative lighting systems have been undergoing strong technology-driven development for some years now. Does this lead to more safety and comfort? Or are these in fact systems no-one really needs? Such questions are not always easy to answer.

The development of new systems is usually geared towards relieving strain on the driver. This implicitly assumes that the driver is under heavy strain, and that relieving this will automatically lead to more safety and comfort. A navigation system that guides the driver through an unfamiliar city at rush hour fulfils this function perfectly.

But what about other situations? Drivers will not always perceive the supposed strain-relief as additional comfort. In fact, new hazardous moments may possibly be generated. Drivers could be tempted to take more risks, and perhaps their attention could wane. This latter case is the so-called vigilance problem. If hazardous moments suddenly occur in such situations, reaction times are usually prolonged. Without question it is extremely important to evaluate innovative systems with regard to comfort, acceptance and safety. As long as there is no comprehensive theory available that predicts drivers' behaviour in relation to all important external conditions, empirical studies are required which record and describe drivers' behaviour.

If a new system is found in theory to be suitable for increasing comfort and safety, the man-machine interface then has to be optimised. Ergonomic evaluations of individual system parameters are necessary for this.

Extensive knowledge of methods is necessary for relevant empirical studies to be carried out (e.g. investigation design, information collection methods, inferential statistical analyses etc.). The greatest challenge however is: how can properties such as safety, acceptance and comfort be made measurable in a numerical form? Here, individual solutions often have to be developed.

This procedure will now be explained in more detail with an example. What colour should the display be on infrared night-vision units? First of all, the principle of infrared night vision units is presented. This is followed by a presentation of the questions to be answered if such a system is to be evaluated. Subsequently, aspects of ergonomics are discussed and the method demonstrated, using the example of display colour.

Analysis of road accidents reveals a high increase in risk in the dark, with limited vision playing a central role. When driving with the dipped beam, detection distances for objects difficult to see – such as pedestrians wearing dark clothes – are so short that the speeds usually driven on country roads are much too high (Locher and Völker 2004). Driving with the main beam is not often possible, as it dazzles other road users. One technical solution to reduce these dangers and increase comfort is an active infrared night-vision system in the vehicle (Kesseler, Kleinkes, Könning 2005). Active systems use infrared lamps on the front of the vehicle, which illuminate the road in a way comparable to the main beam. The wavelength is in the near-infrared range, between 800 and 1300 nm. The reflected radiation is recorded by a camera in the vehicle and the image displayed. Even small objects such as a rabbit or a scarf lying in the road can be clearly detected as sources of danger, even at a distance of 150 m. The representation is done using a grey scale display. Fig. 5.56 shows an example of an image recorded using such a system.

The implementation of such systems in a motor vehicle is linked with quite new questions and problems:

- Are humans really able to process this amount of additional information?
- How long do drivers need to get used to such a system?
- Does the risk of accidents increase during the familiarisation period?
- Do drivers use the increased detection distance to drive even faster, a behaviour known as risk compensation?
- How high is acceptance by the consumer?

Fig. 5.56 Image of a night-vision display

The decision to launch a night-vision system on the market should depend to a major extent on the answers to these questions. A whole series of studies has been performed, resulting in encouraging conclusions. Among other things, an eye-tracking system was used to measure how long the driver's eyes leave the road to collect information from the night-vision display. The times measured were surprisingly short, only a little longer than those for reading the speedometer.

In a second step, the ergonomic parameters have to be optimised. No mistakes may be made here. For example a system that is very good in theory would not be well accepted if an unfavourable position were chosen for the display. Typical questions here are:

- Which display positions on the vehicle interior are suitable?
- How large should the display be?
- What resolution should the display have?
- Which image angle should be represented by the system?
- Which colours are suitable for the representation?

This last question was investigated by the author and Ms Sabrina Schmidt in a study outlined below as an example. As already mentioned, the image is represented in monochrome. It can be in shades of grey, as with old black-and-white television sets, or in any other colour such as yellow, orange, red, green or blue. What influence does the colour have on the driver's detection performance? How can detection performance be made measurable?

A so-called tachistoscopic test was chosen as the instrument of investigation. This is a method where information is presented for a very short time. Test subjects in the laboratory were shown photos on a screen for 1000ms that had been recorded using a night-vision system. These were images of differing complexity, which showed scenes both in built-up areas and in the countryside. The same list of objects appeared on the monitor after every image, and the test subjects had to mark those objects that had been present on the image they had just seen. After a training phase, each test subject had to process twenty such images. In this way, the detection performance of the test subjects was quantified. The following points were of interest:

- the number of correctly identified objects
- the number of objects that were marked although they weren't shown
- the number of completely correctly processed tables (all objects named, none marked wrongly).

The photos were presented in six different colours in line with the task on hand. Luminance and contrast were kept constant. A well-balanced investigation design allowed the detection performance to be determined numerically in relation to the colour presented.

What were the results? There were no differences worth mentioning between the colours presented for all three performance criteria. The analysis of variance carried out did not lead to a significant result either (Locher and Schmidt 2006). Does this mean that all colours are equally suitable? No-because the question of external validity has to be posed for a laboratory experiment i.e. the extent to which the results can be transferred to situations outside the laboratory. There are limitations here. Firstly there are a number of reasons not to use the colour blue. One of these is that accommodation is usually more difficult when looking at blue surfaces than at surfaces of other colours. When driving, accommodation has to take place from a long distance to close-range. In the laboratory however, test subjects always look at the monitor from the same distance. There are also further theoretical limitations for the colour red. People with colour-blindness for red (protanopes), do not have the long wavelength photo pigment. Because of this protanopes not only confuse red and green, but also their vision for red is impaired.

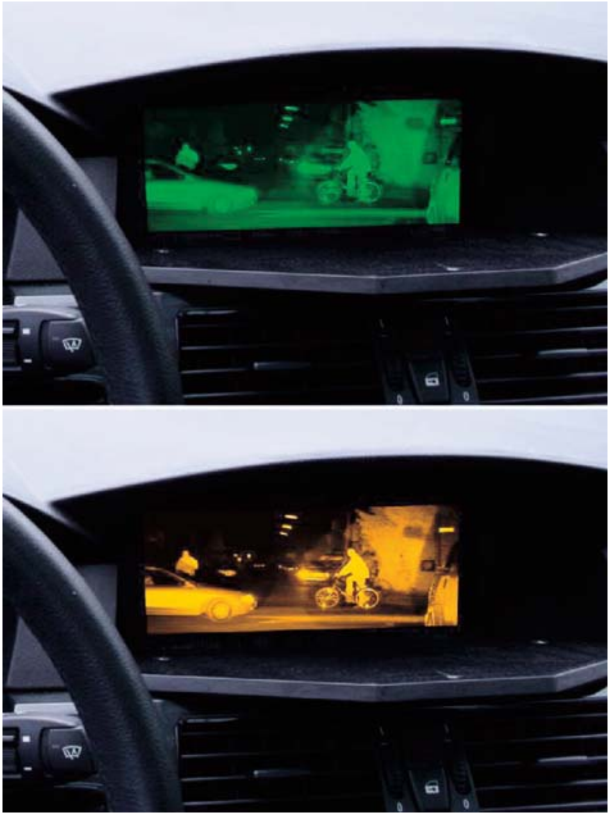


Fig. 5.57 Two examples of coloured night-vision displays

For these reasons, both ends of the colour spectrum should be avoided. The example demonstrates one thing very clearly: empirical investigations alone cannot replace theoretical knowledge!

Alongside detection performance, acceptance was also measured in relation to colour. For this purpose, the test subjects were shown technicolour video films on a monitor. The films had been recorded using a night-vision system. The films were shown in pairs and synchronously, and the test subjects had to say spontaneously which of the films they liked better. All possible pairs were tested. The statements made by the test subjects can be converted into acceptance coefficients. Clear differences were found with regard to preferences.

The example shows that with modern technical systems, tasks in the human factors area are becoming ever more important alongside engineers' development work. There is quite a lot of work involved, but it is certainly worthwhile. The results are systems and interfaces that are optimally adapted to human beings. They can be deduced intuitively from one another and are particularly suited for increasing road traffic safety.

5.6 Active lighting or additional displays? – The principle of immediacy

Let us now come back to the question of whether adding channels is an appropriate means for improving the driver's perception. To this end we will discuss the so-called principle of immediacy.

Evolution has trained us to react appropriately to our environment. One of the most important reaction patterns can be summarised as the principle of immediacy: pay attention to those parts of your body and its environment where your senses indicate that something is happening, and react immediately. When you inadvertently put your hand on a hot plate, you immediately react by pulling your hand away, long before you consciously understand what is happening. A system that displayed the information "Remove your hand immediately from the hot plate", or show a picture of a burning hand would not be very useful.

Perhaps you are wondering what this has to do with automotive lighting. Well, we know that drivers react fastest to the most natural sensory signal. Applied to the question of whether active lighting or an additional information channel should be used at night, it turns out that the most important argument in favour of active lighting, is that it is much more natural to visually perceive objects in the real world environment, rather than on a computer display. The same argument that applies to the hand on the hot plate is valid for dangerous situations in car driving, although in the latter case both the "natural" and the additional "artificial" information channels work on a visual basis.

Under the extreme conditions of driving a car – which is far from being a natural occupation for humans – visual perception is the only human sense that can be used to explore the traffic space. We are much better at recognising a dangerous traffic situation by visual perception of the real scene, than recognition of danger when watching the same scene on a display. For thousands of years our ability to recognise shapes, object detection and motion perception have been trained in the 3D world of our environment. It seems only sensible to rely on this “natural” channel. Active lighting is all about providing the technical means to create lighting conditions such that those objects of the real world that are crucial for driving can be perceived by our natural visual sense.

There are however, situations for example in the case of severe weather conditions (fog, heavy rain or snow), when artificial scenes created on the basis of night-vision or radar systems may provide better information to the driver than the real scene does.

5.7 Lighting future

The field of automotive lighting is complex. Front-lighting, interior lighting, signal lighting and emergency lighting all have their individual specialities, and a wide variety of technologies is applied in each of these areas. The connecting link however, is human vision. All vehicle lighting serves the purpose of enhancing the visual perception of humans. “Lighting is a means to an end”, as one of the authors of this book usually starts his lectures.

The evolution of automotive lighting during the past century went through phases of disruptive technology changes, but also saw periods of smooth development. Front-lighting has already seen the change from the acetylene flame all the way through to high intensity discharge lamps and a huge variety of light distributions. Today most drivers use dipped beam and main beam. The fog lights are an optional extra, and may or may not be fitted in the car. With an advanced front-lighting system there might be an additional town light, bending light or adverse weather light.

The previous chapters gave a comprehensive survey of present day automotive lighting and explained why present day technology, despite its advanced state, is still not sufficient. The preceding section of this chapter finally introduced some of the ideas that are being developed at the moment. What will the future bring for vehicle lighting? We will try to answer this question – if it can be answered at all – considering the fields relevant for automotive lighting:

- Human vision
- Technologies
- Regulations and markets

Our understanding of the processes involved in visual perception is only rudimentary, even though quite a lot is already known. The chapter “How vision constructs reality” described in detail how we construct the world around us from what we see. Taking this knowledge into account, the conclusion is obvious: much can be done to improve automotive lighting.

It is comforting to know that a lot is already being done to improve lighting for cars. The question however remains: are we working on improving the right aspects of automotive lighting? An answer to this question can only be given with the present state of knowledge about human vision and the cognitive processes involved in driving.

Knowledge increases daily on how information enters and is processed by the brain. Modern imaging technologies allow us literally to see how the brain works. Positron emission tomography and functional magnetic resonance imaging can be used to see which regions of our brain are involved in certain processes and how fast signals are being transmitted. Certainly many more interesting breakthroughs can be expected for the near future.

Despite this ever-evolving body of knowledge, there is a sound basis, which allows us to judge the quality of present day and future lighting, from the point of human visual perception. We have a clear understanding of visual attention, detection and tracking of objects, as well as other important aspects in the process of seeing and constructing our environment.

5.7.1 Rating of lighting systems

It is an almost impossible task to give a fair rating of existing lighting without going into details. The different light distributions of headlamps are a good example illustrating this point. Table 5.6 gives an example of how human vision-based criteria might be used in combination with other criteria, such as design or cost, in order to characterise the different light distributions.

Although the scheme looks fairly complete and detailed, it is not. Not all dipped beams are equal. Dipped beams are produced from reflector or projection systems. They may be from Xenon or halogen headlights. Many more details would have to be added to the evaluation scheme in order to satisfy the experts’ wish to be objective.

This scheme might be quite useful however, as it gives a good general characterisation of the different light distributions. The categories: visibility, glare control, guidance, object detection and conspicuousness, already cover some of the more important aspects of human visual perception with respect to driving. As can be clearly seen from Table 5.6, amongst the existing light distributions not one is perfect.

Table 5.6 Example of a simple rating scheme for light distributions

	visibility	glare control	guidance	object detection	conspicuousness
headlamp function					
dipped beam	+	+	-	-	+
main beam	++	--	+	+	++
town light	o	++	-	--	+
bending light	++	+	o	+	o
adverse weather light	+	++	+	o	+
high beam assist	+	++	+	+	o
segmented low beam	+	++	-	-	o
fixation assist	++	o	o	++	o
colour weighted dipped beam	+	+	o	++	+
pixel light	++	++	+	+	+

If it is difficult to rate something which already exists. How much more difficult is it then to rate something still being developed, where the time of availability of the first prototypes is not known, and it is not known whether the development will be successful at all?

The first veto to the question of success or failure comes from technology. If the technology is not available, not reliable or simply too expensive, then a new lighting function based on this technology will not make it into the market.

A second veto can come from regulations. If the custodians of society cannot be convinced that the new lighting function under consideration really has benefits, and not more disadvantages than advantages for society, then even the best technology will not make it into the market.

The next spotlight looks at regulations and related subjects.

Spotlight

A day in the life…

Automotive lighting is highly regulated. It is governed historically by state, national and international law. In order to avoid confusion, many nations are opting to join one of the international regulations. As a result, vehicle lighting is slowly becoming more and more global, with similar or identical equipment specification, test and approval procedures. A small community of experts try to hold together lighting standards, sometimes against the diverse interests of individual member states, sometimes against a flood of technology or market-motivated innovation.

The final decisions on regulations for lighting are taken by a government official. They rarely make these decisions alone, but rely on advice from lighting experts. Needless to say, automotive suppliers assist in the preparation of regulatory work. For the lighting expert advising the international regulatory committee, the following list represents a typical cross section of topics:

- AFS (adaptive front-lighting system)
- NFF (new front fog light)
- Front fog light facelift
- P (S) 24 W, H21 W for front fog light
- LED sources in headlamps
- Double-source main beam
- Dipped beam upgrade
- Harmonised dipped beam
- Harmonised main beam
- Signal light variable intensities
- EuroNCAP – headlamp assessment

The regulation work is a mixture of standardisation, implementing or enforcing political directives and improving safety.

Standardisation for automotive lighting starts with the light sources. As most light sources wear out, replacement bulbs have to be readily available. Lighting regulations ensure standards for replaceable bulbs, durability of lens materials, colours of signals, dimensions of lit areas, distances between competing signal functions, mounting height of lamps, light distributions and so on.

Lighting regulations also accommodate political interests. For example, the heightened awareness for recycling led to the ‘end of life directive’ for vehicles, which defines and limits the materials to be used in cars. The movement for the protection of pedestrians has led to the introduction of new regulations, which affect the characteristic of the vehicle front-end and change the design requirements for headlamps. Lobby groups, test houses for consumer goods and research institutes can influence the direction in which regulations progress.

The most important role of the regulations is to ensure safety standards for cars and traffic. Automotive lighting plays a significant role in the reduction of accident risk. Looking at the ECE regulations it is not surprising that a good portion is dedicated to lighting. As technology is enabling further improvements in lighting, the safety aspect will continue to motivate changes in today's lighting regulations.

Regulations are rarely made overnight. The rule-making body is very international and the process of arriving at a joint consensus takes time. So many of the changes we can expect to see in the next generation of vehicles, are going through their preparatory stages today. The more imminent future of lighting is already visible in the working groups of the international standards organisation.

Table 5.7 (Speculative) roadmap of lighting improvements for regulations

Year	**Event**
2007	First LED headlamp for dipped beam
2007	Full AFS regulation
2008	Ambient interior lighting
2008	Xenon without mercury becomes mandatory
2009	European approval for LED fog and headlamp
2009	Forward looking or navigation assisted AFS headlamp
2009-12	Day time running light becomes wide spread and even mandatory
2010	Pedestrian protection phase 2
2012	Night designs become trade mark
2015	42 Volt vehicle electronics

5.7.2 Recommendations

Let us focus for a moment on the most important customer of automotive lighting, the human visual system, ignoring all other aspects. What would then be the recommendations for future lighting systems for vehicles?

For a moment we will ignore the high prices of DMD-chips and the fragility of scanner systems, and ignore questions about when a given lighting function may be approved by legislation. Let us simply ask what the doctor orders – no matter if the medicine already exists and no matter how expensive it might be.

Table 5.8 Rating of improved or new future lighting functions

	guidance	object detection	glare control	immediate traffic information
improved lighting function				
• advanced front lighting system	bends/ motorway		town	
• adaptive signal lights				deceleration
• marker light		for detected objects		
new lighting functions				
• contour light				position, direction, speed
• cooperative lighting	in medium and heavy traffic			
• signal tuning			indicator	brake
• ‘facial’ change				e.g. stop and go
• glare-free main beam (pixel light)	as for main beam		for detected objects	

We will also focus only on the high level vision tasks for driving, such as:

- Guidance – knowing where the road goes
- Object detection – knowing where obstacles are
- Glare control – giving other traffic members a chance to see without being dazzled
- Immediate traffic information – knowing what is going on in the immediate vicinity

Then a clear recommendation can be made with respect to improving existing lighting functions and establishing new functions as shown in Table 5.8. In summary, from the point of view of human vision, all of the above lighting functions can therefore be recommended:

- Advanced front lighting systems (AFS):
  Changing the light distribution for country, town, motorway, adverse weather and bends in the road will improve significantly visual guidance and object detection, without adversely affecting glare.
- Adaptive signal lights:
  Can alert the immediately following vehicle for example, to sudden braking or emergency stops.
- Marker lights:
  Can alert the driver to objects, which are liable to impede the path of the vehicle.
- Contour lighting:
  A vehicle with contour lighting is recognised sooner and more intuitively; its position, direction of travel and speed easily become familiar without the need for conscious observation.
- Cooperative lighting:
  Headlamps are developed with little consideration for the typical, dense traffic situations we have today. Road and traffic lighting can be affected by communal street lighting, collaborative lighting or platoon lighting.
- Signal tuning:
  LED signal lights have instant response characteristics. We can tune LED signals to produce an attention flash for the first signal or even provide a subliminal alert prior to emergency braking.
- Facial change:
  Now that it is known that processing of faces and facially expressed moods takes place in dedicated centres of the brain, perhaps it is possible to change the “facial expression” of the rear of the car when braking? Or use could be made of an intuitive display for stop and go? Or the indicator could be given an additional movement?

It is now clear that human beings are not designed for nocturnal driving. The automotive industry has made a huge effort to compensate for this, such that today’s vehicle lighting is probably the optimal compromise. Despite this, automotive lighting systems fall short of the optimal. A high price is paid in terms of risk, driving stress, anguish over minor mishaps and deep sorrow over major accidents. The financial loss incurred with accidents is a small indicator of how much is still left for us to do in order to improve automotive lighting.

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