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Final thesis

LED technology in automotive headlamps: driving more safely with adaptive lighting systems

Supervisor:

Prof. Guido Albertengo

Company Supervisor:

Dr. Magistrale Alberto Pairetti

Candidate:

Dr. Dorian Cerri

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Contents

Introduction

This thesis is focused on automotive headlamps, explaining in detail the adaptive lighting systems especially the matrix systems and high definition headlamps. I personally believe that this technology will lead to safety improvements on the night driving conditions. To allow the understanding of matrix technology some basic knowledge on the automotive headlamps are necessary. Starting from the simplest application and evolving to the most complicated ones. When I said that the matrix technology will improve the safety on our roads, it's not because this technology is not yet implemented on series vehicles but because the percentage of the vehicles equipped with matrix headlamp is still very low. As always the most advanced technologies are reserved only for some versions of premium vehicles due to cost targets. But what is our role as engineers? Obviously the engineering community couldn't help the car makers financially to implement the matrix technology on the headlamps but could for sure increase the awareness of the users towards this technology. Talking, explaining and demonstrating the advantages of such important improvement in safety will create a desire to the final users to use the matrix technology for themselves and the others in their vehicles. Time is a very important factor in technology allowing as the years go by to reduce as much as possible the cost for implementation. I want to remember the example of ABS systems, that started with implementation on the premium vehicles, then expanded the application in all the vehicles and finally become obligatory to every vehicle by the norms. My wish for the matrix technology is to be available even to the cheaper vehicles in order to increase the safety on the roads. Briefly I'am going to explain how this document is organized in order to have an overview on the topic:

- Chapter 1: the main lighting sources used in automotive headlamps will be discussed. The principal topic are the LEDs, which will be analysed in detail. Starting from halogen bulb going on with HID (high intensity discharge) bulb, discussing briefly functionality and limitation

- Chapter 2: describe the headlamp as a product explaining typical technical solutions components and lighting functions. The standards for homologation will be explained and also the diagrams for performance benchmarking will be discussed. The last part will be dedicated to the new generation LEDs packages implemented in automotive headlamps. A solid idea of this product will be created to the reader, in order to be ready for the next step, introduction to the matrix technology.

- Chapter 3: The third chapter is the core of this thesis since the matrix technology will be analysed. Starting from the older systems and finishing with the last ones. Some examples of implementation, laboratory testing, and feedback from customers will be discussed. LED module of Mazda CX5 and E-light module developed from Automotive Lighting will be analysed this with the aim of showing how different suppliers realize the full LED modules. Pixel lighting solution is reachable by incrementing the number of LED in the module and managing the LEDs separately in order to create the matrix windows. An important example is the cost reduction politics adopted by Renault aiming to the extension of the full LED headlamps also for non premium vehicles. At the end two examples of high definition headlamp will be showed.

- Chapter 4: At the end the last chapter will be projected to the future, analyzing autonomous driving and lighting. This topic is new but autonomous vehicles present in the near future will transform also the lighting field. New challenges will bring new solutions on the lighting request of these vehicles.

Chapter 1

Lighting sources on headlamps

There are several typologies of headlamps in automotive industry, usually the division is due to the differences of light source used. Obviously every headlamp is different on each car model but this only from a stylish point of view, as will be showed on this thesis hereafter, each headlamp assembled on every vehicle circulating on our roads could be classified within 4 big categories: Halogen, HID, LED, Laser.

Figure 1.1: full LED headlamps

Figure 1.2: HID headlamps

These categories do not represent only the evolution in time of headlamps industry but also different optionals and/or segments offered by car makers. Halogen, HID, LED, Laser headlamps offer different performances from a lighting point of view, constrains stylists differently and has different cost. Before explaining performances and costs let's start to understand the technological differences between light sources applied on these headlamps technology.

1.1 Halogen light bulb

The core of Halogen headlamp is the halogen light bulb where the light is generated. As the current flow on the circuit (red arrows) the filament emit light due to its high temperature. The halogen light bulb is an advance version of incandescent bulbs that has been used since the invention of the electric light. More in detail the halogen light bulb is called tungsten halogen lamp this because the filament is composed of ductile tungsten.

Figure 1.3: Halogen light bulb

This type of bulb has gone through an evolutionary process since the beginning of the 20 th century. The reason why this type of filament was advantaged than the incandescent bulb was due to the generation of brighter light and longer duration, anyway tungsten filament has faced challenges as the years passed by. On the first version the tungsten filament, contained in vacuum glass, evaporated quickly during operation at a rate that increased with operating temperatures. Higher lighting brings higher temperatures of the filament which increases tungsten evaporation and all this mechanism leads to e reduction of bulb life, as the tungsten evaporated from the filament. In this situation the designer has to made a trade off between light performance and bulb longevity. As the tungsten evaporated off the filament it would condense on the inner surface of the bulb darkening the glass and blocking the light output. Another step in the evolution were the applying of inert gas like argon instead of vacuum, this solution permit the reduction of tungsten evaporation and prolong the filament life, however the argon gas also cooled the filament and reduces its efficiency, so this solution still wasn't perfect. The last evolution was made in the 1950s using halogen elements such as iodine and bromine inside the bulb instead of inert gases.

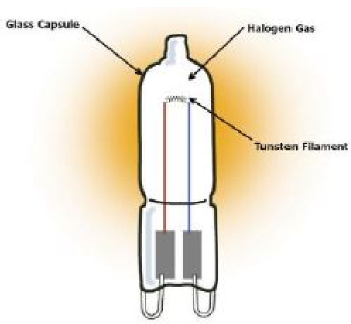


Figure 1.4: Main elements of a halogen light bulb

The inert gas is at high pressure inside the bulb around 7- 8 bar. The glass capsule is composed of quartz SiO_2 because it has to resist higher temperatures during lamp functioning, but the quartz composition could lead to devitrification process. The primary cause of devitrification is the contamination of quartz: typically refers to the introduction of alkali to the quartz. Alkali's include sodium, potassium and lithium and are usually introduced to the quartz as a result of contact with the oils present in the skin. So simply by touching the surface of the quartz with bare hands could contaminate the quartz. A catalyst must be present to start the process and in the case of quartz, the catalyst is heat, specifically 1000 °C. It is interesting to note that contamination may also be introduced to the quartz by way of water. Water drops on the surface of the quartz may attract contaminants and, when dried, the contaminants may remain on the surface of the quartz. Devitrification leads to the loose of transparency of the quartz and also the reduction of the bulb life because it can explode. Halogen gas and tungsten filament combine to produce a chemical reaction called "the halogen cycle". This cycle permit a big advantage in terms of performance and longevity of the bulb.

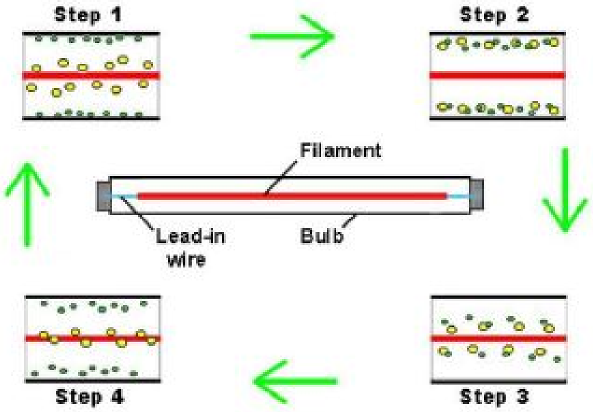


Figure 1.5: The halogen cycle

There are fou rmain steps in the halogen cycle as described below:

- Step 1: Tungsten vaporizes at high temperatures
  As the bulb is switched on the current starts flowing through the tungsten filament heating it up rapidly. The filament, the inert gas and the bulb surface are at different temperatures and this condition creates convective currents inside of the bulb. As the tungsten filament reaches 2500 °C tungsten atoms starts vaporizing. In the case of bulbs without halogen gas the vaporized atoms deposit in the bulb's inner surface, blackening it and thinning the filament, reducing the life of the lamp.

- Step 2: Creation of Tungsten Halide
  The halogen atoms react with the vaporized tungsten and form tungsten oxyhalide or tungsten halide compounds. Thus vaporized tungsten isn't allowed to be deposited on the bulb surface. The bulb surface temperature has to be more than 250 °C for the halogen cycle to trigger into action.

- Step 3: Movement of the halide compounds
  The halide compounds get in the convection currents, created due to the temperature gradient and get directed towards the filament.

- Step 4: Deposition of Tungsten back to the filament
  When the tungsten halide compounds come in contact with the filament, the high temperatures makes the halides dissociate again, depositing tungsten back to the filament. The vaporized halogen gas is able again to catch more tungsten

atoms and redeposit it on the filament, of course the tungsten atoms vaporized from a certain region of the filament are rarely deposited at the same place. As a result of this uneven deposition the filament is going to break at some point of time during usage, still the halogen cycle, slows down this process quite substantially.

The tungsten filament bulb has a greater performance than the other types of bulbs described previously since it works in higher temperatures and also these higher temperatures trigger the halogen cycle ensuring a longer life.

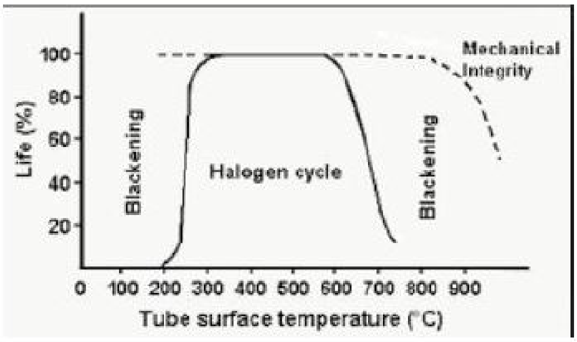


Figure 1.6: Temperature vs performace for a tungsten filament bulb

1.2 HID - high intensity discharge

Figure 1.7: 35W HID lamp

On HID lamps instead of passing electricity through a filament to produce light, the electricity arcs between two electrodes(elements 4 and 5 Figure 1.8) inside the bulb. Going more in detail there is a special quartz bulb that contains no filament, filled with xenon gas and a small amount of mercury and other metal salts. Inside the bulb are two tungsten electrodes separated by a small gap (about 4mm). When high voltage current is applied to the electrodes excites the gases inside the bulb and forms an electrical arc between the electrodes. The hot ionized gas produces a “plasma discharge” that generates an extremely intense, bluish white light. Once ignited, the pressure inside an HID bulb rises over 30 bar due to heat, this creates a potential explosion hazard. HID bulbs require a high voltage ignition source to start, typically takes up to 25000 Volts to start a xenon bulb, but only 80 to 90 Volts to keep it operating once the initial arc has formed. The normal 12 Volts DC from the vehicle’s electrical system is stepped up and controlled by an igniter module and inverter (ballast), which also converts the voltage to AC which is necessary to operate the HID bulb. The ballast adjust the voltage and current frequency to operating requirements. The AC ballast frequency is usually in the 250 to 450 Hz range. When HID bulb are turned on, the light appears more bluish but become quickly brightness as the bulb warms up.

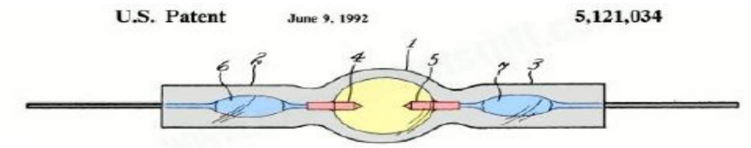


Figure 1.8: internal bulb components

The lamp is composed of a tubular outer bulb approximately 10mm in diameter (element 1, 2 and 3 Figure 1.8) which contains the arc tube (inner bulb). The outer bulb is made of special quartz such as cerium doped quartz which blocks most ultraviolet, especially the more dangerous short and medium wavelength as well as much of the 365, 366 nm longwave mercury line cluster.

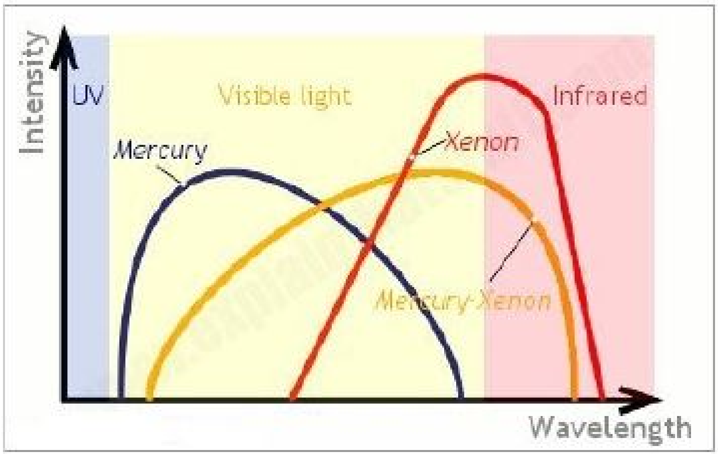


Figure 1.9: Light composition of HID elements

HID lamps are more efficient than halogen lamps because they emit more light with less energy consumption, also they last longer ,around 2000h, than halogen with a duration of 200 - 400h. Wear usually is due to on/off cycles versus the total on time. The highest wear occurs when HID lamp is ignited while still hot and before the metallic have recrystallized. At the end of life HID lamps exhibit a phenomenon known as cycling. As the lamp gets older the voltage necessary to maintain the arc eventually rises to exceed the voltage provided by the electric ballast.

1.3 LED - light emitting diode

LED produce light according to a phenomenon called electroluminescence, this is an optical and electrical phenomenon in which a material emits light in response to the passage of an electric current or to a strong electric field. Before showing how a typical LED for automotive application is made lets start explaining PN juction that is the basis of working principle for every LED. Studing PN juction will lead to a better understanding of LED for autmotive that are more complicated due to some important request that will be showed later.

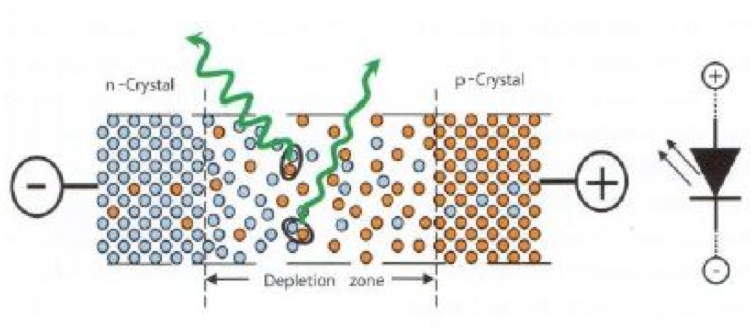


Figure 1.10: LED working principle

p type and n type are two semiconduct or materials, obtained by doping insulating materials. Silicon is an insulator material but if atoms of antimony are added this could lead to the capacity of electricity conduction, silicon altered in this way is called n type (negative type) because extra electrons can carry negative electric charge through it. In the same way if boron atoms were added electrons are taken from the silicon and "holes" where electrons should be are created, silicon altered in this way is called p type (positive type) because the holes can move around and carry positive electric charge.

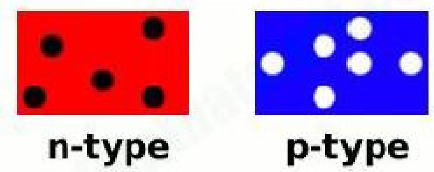


Figure 1.11: insulating materials altered as negative and positive type

A junction is created between n-type silicon (with slightly too many electrons) and p-type electron (with slightly too few electrons), in this case some of the extra electrons in the n-type will nip across the join (which is called junction) into the holes of the p-type so, either side of the junction, normal silicon will be formed again with neither too many electrons nor too few electrons in it. Since ordinary silicon doesn't conduct electricity, nor does this junction. It becomes a barrier between the n-type and p-type silicon and it is called a depletion zone because it contains no free electrons or holes.

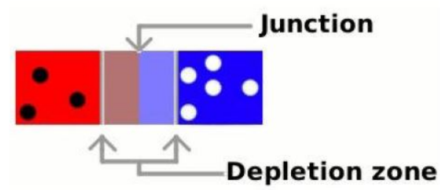


Figure 1.12: p-n junction

Suppose to connect a battery to this p-type/n-type junction. If the negative terminal is connected to the n-type silicon and the positive terminal is connected to the p-type silicon the depletion zone shrinks drastically. Electrons and holes move across the junction in opposite direction and a current flows, this configuration is called forward-bias.
If the current is reversed, the depletion zone gets wider. All the holes push up toward one end, all the electrons push up to the other end, and no current flows at all, this is called reverse bias.
This is the key concept of how a diode works and why the electric current is allowed to

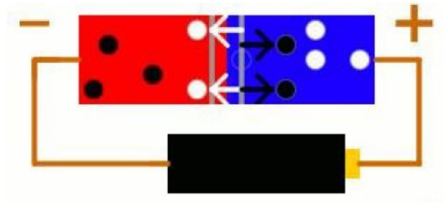


Figure 1.13: p-n junction in a forward-bias configuration

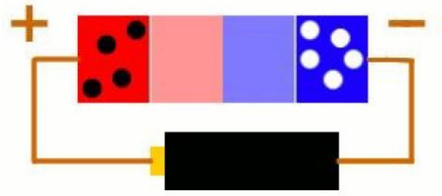


Figure 1.14: p-n junction in a reverse-bias configuration

flow only one way. LED is a simply diode that are designed to produce light. In a forward-biased configuration electrons and holes are zipping back and forth across the junction, they're constantly combining and wiping one another out. Sooner or later when the electron will move from the n-type into the p-type silicon, it will combine with a hole. That makes an atom complete and more stable and it gives burst of energy so a photon of light is produced. At this point the basic concept on the functioning of LED is explained, we must take in consideration that the LEDs used in automotive HL works with the same principle but with different materials and technologies, this mainly for two reasons:

1. To illuminate the road ahead of a vehicle powerful LED are necessary.
2. LED must produce white light.

White light is produced using a phosphor material to convert light from a blue LED to a broadspectrum white light. The yellow phosphor is cerium-doped YAG crystals coated on the LED. The YAG phosphor causes white LEDs to look yellow when off. The "whiteness" of the light produced is engineered to suit the human eye. The blue LED generally is an Indium gallium nitride (InGaN) that is a semiconductor material made of a mix of gallium nitride (GaN) and inidium nitride (InN). InGaN is grown on a GaN buffer on a transparent substrate as sapphire or silicon carbite. So the InGaN semiconductor is coated with $Y_3\ Al_5\ O_{12}$:Ce known as "YAG" cerium doped phosphor coating produces yellow light through fluorescense. The combination of that yellow with remaining blue light appears white to the eye. So in conclusion just to keep in mind the basic concepts: In a LED the recombination of electrons and electrons holes in a semiconductor produces light, this process is called electroluminescense. The wavelength of the light depends on the energy band gap of the semiconductor used. Selecting different semiconductors materials, single color LEDs can emit light in a narrow band of wavelength from near-infrared through the visible spectrum and into the ultraviolet range. As the wavelength become shorter, because of the larger band gap of these semiconductors, the operating voltage of the LED increases. The figure below shows how a blue LED is made in detail. There are several layers placed one above the other, in this case the light is produced downwards.

In the Figure 1.15 are showed the following layers, take in consideration that LED emits light downward in this case:

1. sapphire substrate
2. aluminum nitride buffer layer
3. n-type made from gallium nitride doped with silicon
4. semi-insulating, semi-p-type layer made from indium gallium nitride
5. p-type aluminum gallium nitride clad layer
6. p-type layer made of gallium nitride doped with magnesium
7. aluminum positive electrode
8. aluminum negative electrode
9. insulating groove between electrodes

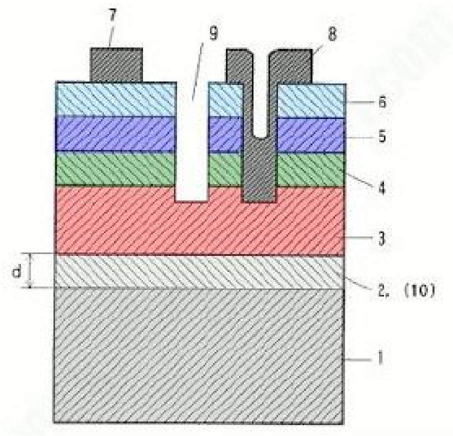


Figure 1.15: Blue LED structure

The LED is soldered on a flip circuit in order to supply the current and assembly the circuit on the headlamp.

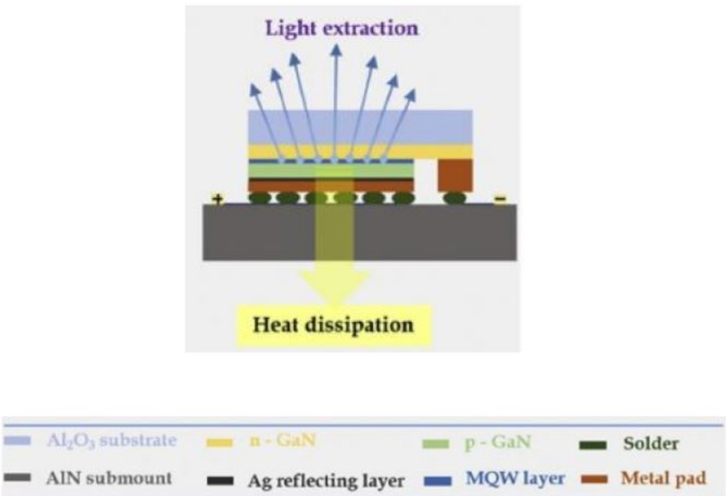


Figure 1.16: Blue LED for automotive application

1.4 Light as wavelength

At this point of the thesis the differencies between three main light sources were explained. Halogen, HID and LED light could be used in automotive headlamps based on different requests of the project under development. In order to understand better from a physic point of view the difference in illumination between the different light sources used in automotive headlamp technology a fast introduction to the light as an electromagnetic wave will be described. The light is an electromagnetic radiation within a certain portion of the electromagnetic spectrum, which can be detected by the human eye. Visible light has a wavelength in the range of 400-700 nm.

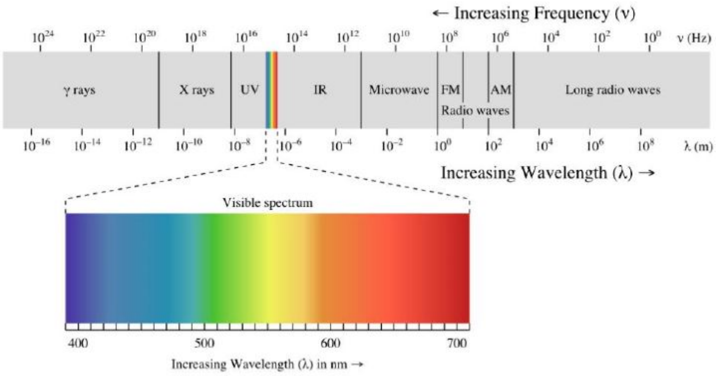


Figure 1.17: Light in different electromagnetic wavelength

Light is measured with two alternative sets of unit:

1. Radiometry, consists of measurements of light power at all wavelengths (not used in automotive lighting)

2. Photometry measures light with wavelength weighted with respect to a standardized model of human brightness perception. Photometry is useful to quantify illumination intended for human use as lighting in automotive.

The color temperature of a light source is the temperature of an ideal black body radiator that radiates light of a color comparable to that of the light source. Color temperature is a characteristics of visible light that has important applications in lighting. In practice, color temperature is meaningful only for light sources that do in fact correspond somewhat closely to the radiation of some black body i.e, light in a range going from red to orange to yellow to white to blueish white, it does not make sense to speak of the color temperature of, e.g a green or a purple light . Color temperatures is conventionally expressed in kelvins, using the symbol K, a unit of measure for absolute temperature. Color temperatures over 5000K are called "cool colors" (bluish), while lower color temperatures (2700-3000 K) are called "warm colors" (yellowish). "Warm" in the context is an analogy to radiated heat flux of traditional incandescent lighting rather than temperature. The spectral peak of warm-colored light is closer to infrared, and most natural warm-colored light sources emit significant infrared radiation. In this way is possible to define a standard by which light sources are compared. An incandescent lamp's light is thermal radiation, and the bulb approximates an ideal-body radiator, so its color temperature is essentially the temperature of the filament. Thus a relatively low temperature emits a dull red and a high temperature emits the almost white of the traditional incandescent light bulb. Other sources like fluorescent lamps or LED emit light primarily by the processes other than thermal radiation. This mean that the emitted radiation does not follow the form of the black-body spectrum. These sources are assigned what is known as correlated color temperature (CCT). CCT is the color temperature of a black-body radiator which to human color perception most closely matches the light from the lamp.

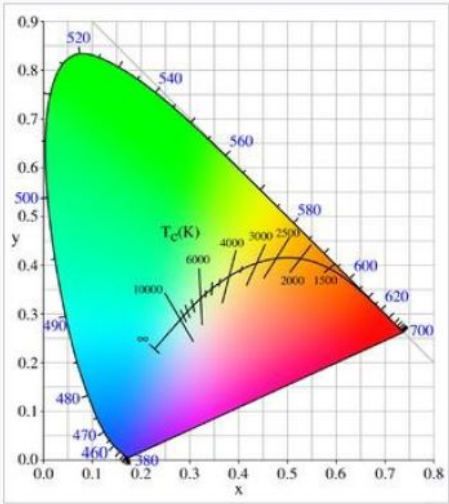


Figure 1.18: Chromaticity space, lines of constant angle correlated color temperature

Chapter 2

Automotive headlamp characteristics

After the explanetion of the light sources used on automotive headlamps in this second chapter the focus will be on the headlamp as a product. Starting from a typical construction and going on with the functions and regulations for homologation. Although every project is different there is a similarity or a general configuration that will help the reader to create an idea and also to understand better all the other sections.

2.1 Headlamp main components

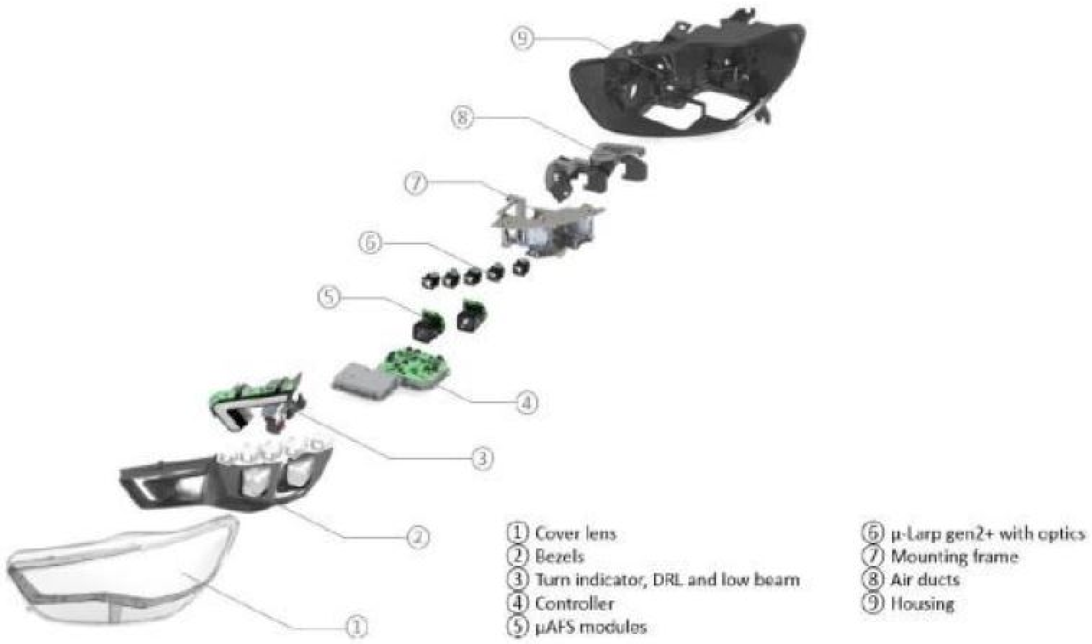


Figure 2.1: Headlamp components

In the following a typical headlamp configuration will be described, but different projects could used different solutions. The housing component (nr.9 on figure19) is the base element because main subassemblies are mounted on the housing also the housing allows the assembly on the vehicle. The housing is made of polypropylene and is produced by a moulding process. The assembly of the headlamp on the vehicle chassis is realized through screws. The main illumination subassembly is the core of the headlamp (nr. 5, 6, 7, 8 on figure19), this subassembly could be composed of a full LED module or a HID module or an halogen reflector with bulbs or other solutions. Different technical configurations contains always the main components analysed below:

- ligh souce could contain one typology of the following but also a mix of them :
  - LED
  - HID bulb
  - halogen bulb
- optics, define the light distribution ahead of the vehicle because the light distribution is subjected to homologation regulations:
  - lens (PMMA, PC or other material)
  - reflector, are made of the BMC moulded and then alluminated in order to be reflective.
- the frame : allows the assembly on the housing, allows regulations (vertical and horizontal adjustment)
- electronics: management of the LEDs or HID.

Other functions like turn indicator, DRL and position are realized through other LEDs assembled on PCBs not inside the module. This is due to the fact that even the same LED module could be used on different headlamp models without compromising too much the style, DRL, turn indicator and position are designed personalized for each model considering brand and style requests. The main illumination subassembly is mounted on the housing through three points, one fixed, the second is the vertical regulation and the last the horizontal regulation. The regulations are realized using a screwing mechanism. These regulations could be controlled also by electric motors. An ECU (nr.4 on figure 19) is mounted on the housing through screws, generally it interfaces the body computer the vehicle the LEDs module and the other functions. Bezels (nr.2 on figure 19) are used to create the aesthetics of the headlamp, to cover components on the aesthetical parts and for assembly purposes. The main bezel is the last component screwed on the housing after that the lens is glued on the housing. Usually lens is made of polycarbonate that guarantee the transparency needed for optical reasons, also it guarantees the protection from external factors.On the headlamp housing the are some ventilation holes generally covered by membranes. These membranes allows the passage of air but not the water. These holes are the only contact point of the headlamp internal with external environment. There is necessity to allow air passage in order the balance the air pressure that change in function of the internal temperature.

2.2 Headlamp lighting functions

The lighting functions are divided in two groups:

1. Illumination functions are the functions in charge of illuminating ahead of the vehicle, so the light need to be powerful enough in order to guarantee the visibility in worst cases for example dark, fog, heavy rain, ecc. In this group there are the following functions:

- Low-beam, illuminate ahead of the vehicle without glaring the other road users.
- High-beam, illuminate ahead of the vehicle but glare the other road users.
- Fog, illuminate ahead of the vehicle in case of fog.
- Cornering, illuminate the turning zone of the vehicle when the vehicle is turning.

2. Signaling functions are the functions that signal something to the other road users. In this group there are the following functions:

   - Position, signal the presence of the vehicle to the other road users. This function is used always with the low beam function.
   - Turn indicator, signal the intention of the vehicle to change direction.
   - Side marker, in the NAFTA market indicate the presence of the vehicle. This function is placed on the side of the vehicle.
   - DRL (daytime running light), signal the presence of the vehicle during the day so without the low beam running.

2.3 Regulations in EMEA region

In the EU area regulation 112 specifies the main characteristics of the headlamp. In this part more details will be given regarding to the illumination characteristics necessary for the various functions of the headlamp. The luminous intensity produced by the headlamp shall be measured at 25 m distance by means of a photoelectric cell having a useful area comprised within a square of 65 mm side. The point HV is the centre-point of the coordinate system with a vertical polar axis. Line h is the horizontal through HV.

2.4 Low beam

Low beam (dipped beam, passing beam, meeting beam) headlamps provide a distribution of light designed to provide forward and lateral illumination, with limits on light directed towards the eyes of other road users to control glare. This function is intended for use whenever other vehicles are present ahead, whether oncoming or being overtaken. The international ECE Regulations for filament headlamps and for high-intensity discharge headlamps specify a beam with a sharp, asymmetric cut off preventing significant amounts of light from being cast into the eyes of drivers of preceding or oncoming cars. Control of glare is less strict in the North American SAE beam standard contained in FMVSS / CMVSS 108. The luminous intensity distribution of the principal passing-beam headlamp shall incorporate a "cut-off" (see Figure 2.3), which enables the headlamp to be adjusted correctly for the photometric measurements and for the aiming on the vehicle.
The "cut-off" shall provide:

- For right hand traffic beams:

  1. A straight "horizontal part" towards the left;
  2. A raised "elbow – shoulder" part towards the right.

- For left hand traffic beams:
    1. A straight "horizontal part" towards the right;
    2. A raised "elbow - shoulder" part towards the left.

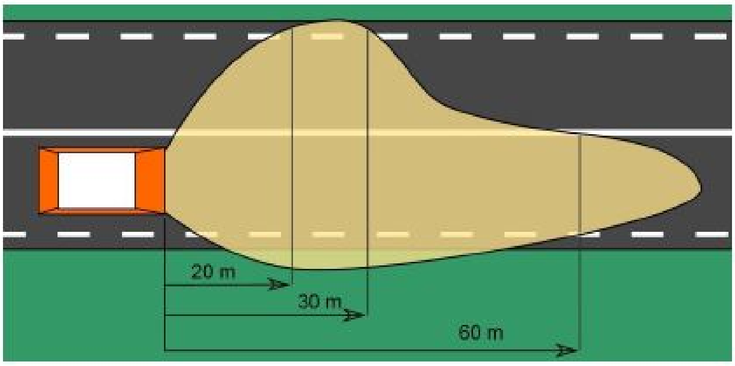


Figure 2.2: Low beam distribution, top view

In each case the "elbow-shoulder" part shall have a sharp edge. The headlamp shall be visually aimed by means of the "cut-off" (see Figure 2.3) as follows. The aiming shall be carried out using a flat vertical screen set up at a distance of 10 m or 25 forward of the headlamp and at right angles to the H-V axis. The screen shall be sufficiently wide to allow examination and adjustment of the "cut-off" of the passing-beam over at least 5° on either side of the V-V line. For vertical adjustment: the horizontal part of the "cut-off" is moved upward from below line B and adjusted to its nominal position one per cent (0.57 °) below the H-H line. For horizontal adjustment: the "elbow – shoulder" part of the "cut-off" shall be moved. For right hand traffic from right to left and shall be horizontally positioned after its movement so that:

- Above the line 0.2° D its "shoulder" shall not exceed the line A to the left
- The line 0.2° D or below its "shoulder" should cross the line A
- The kink of the "elbow" is basically located within +/-0.5 ° to the left or right of the V-V line

Or for left hand traffic from left to right and shall be horizontally positioned after its movement so that:

- Above the line 0.2 D its "shoulder" shall not exceed the line A to the right
- On the line 0.2° or below its "shoulder" cross the line A
- The kink of the "elbow" should be primarily on the V-V line

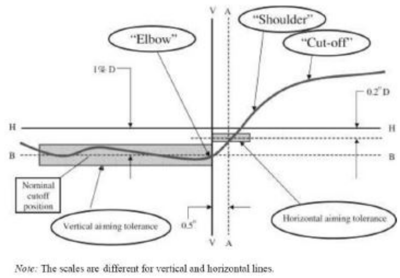


Figure 2.3: Low beam cut off line distribution, projection on screen

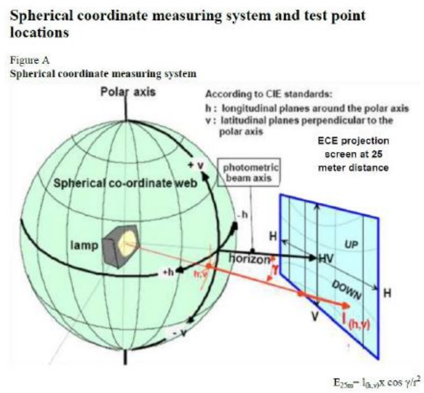


Figure 2.4: Reference system used by homologation regulation

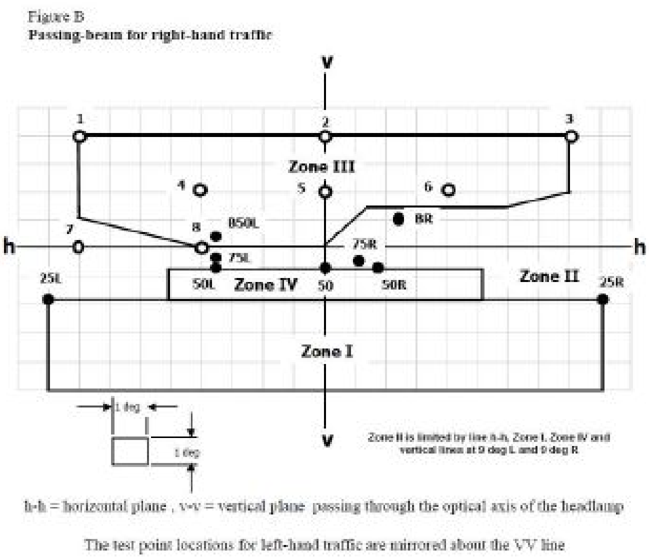


Figure 2.5: Low beam distribution regulation, projection on screen

The passing-beam shall meet the luminous intensities at the test points referred to in the figure 2.6

<table>
<tr><th colspan="7" rowspan="1">Headlamps for RH Traffic**</th><th colspan="2">Class A Headlamp</th><th colspan="2">Class B Headlamp</th></tr>
<tr><th colspan="3" rowspan="2">Test point designation</th><th colspan="4" rowspan="2">Test point
angular coordinates - Degrees</th><th colspan="2">Required luminous intensity
cd</th><th colspan="2">Required luminous intensity
cd</th></tr>
<tr><th>Max</th><th>Min</th><th>Max</th><th>Min</th></tr>
<tr><td colspan="3">B 50 L</td><td colspan="4">0.57U, 3.43L</td><td>350</td><td></td><td>350</td><td></td></tr>
<tr><td colspan="3">BR</td><td colspan="4">1.0 U, 2.5R</td><td>1,750</td><td></td><td>1,750</td><td></td></tr>
<tr><td colspan="3">75 R</td><td colspan="4">0.57D, 1.15R</td><td></td><td>5,100</td><td></td><td>10,100</td></tr>
<tr><td colspan="3">75 L</td><td colspan="4">0.57D, 3.43L</td><td>10,600</td><td></td><td>10,600</td><td></td></tr>
<tr><td colspan="3">50 L</td><td colspan="4">0.86D, 3.43L</td><td>13,200***</td><td></td><td>13,200***</td><td></td></tr>
<tr><td colspan="3">50 R</td><td colspan="4">0.86D, 1.72R</td><td></td><td>5,100</td><td></td><td>10,100</td></tr>
<tr><td colspan="3">50 V</td><td colspan="4">0.86D, 0</td><td></td><td></td><td></td><td>5,100</td></tr>
<tr><td colspan="3">25 L</td><td colspan="4">1.72D, 9.0L</td><td></td><td>1,250</td><td></td><td>1,700</td></tr>
<tr><td colspan="3">25 R</td><td colspan="4">1.72D, 9.0R</td><td></td><td>1,250</td><td></td><td>1,700</td></tr>
<tr><td colspan="7">Any point in zone III
(bounded by the following coordinates in degrees)</td><td rowspan="3">625</td><td rowspan="3"></td><td rowspan="3">625</td><td rowspan="3"></td></tr>
<tr><td>8 L</td><td>8 L</td><td>8 R</td><td>8 R</td><td>6 R</td><td>1.5 R</td><td>V-V</td></tr>
<tr><td>1 U</td><td>4 U</td><td>4 U</td><td>2 U</td><td>1.5 U</td><td>1.5 U</td><td>H-H</td></tr>
<tr><td colspan="7">Any point in zone IV
(0.86D to 1.72D, 5.15 L to 5.15 R)</td><td></td><td>1,700</td><td></td><td>2,500</td></tr>
<tr><td colspan="7">Any point in zone I
(1.72D to 4D, 9 L to 9 R)</td><td>17,600</td><td></td><td>< 2I*</td><td></td></tr>
</table>

Figure 2.6: Low beam homologation values

2.5 High beam function

High beam (main beam, driving beam, full beam) provide a bright, center-weighted distribution of light with no particular control of light directed towards other road users' eyes (see fugure 2.7 and 2.8). As such, they are only suitable for use when alone on the road, as the glare they produce will dazzle other drivers.

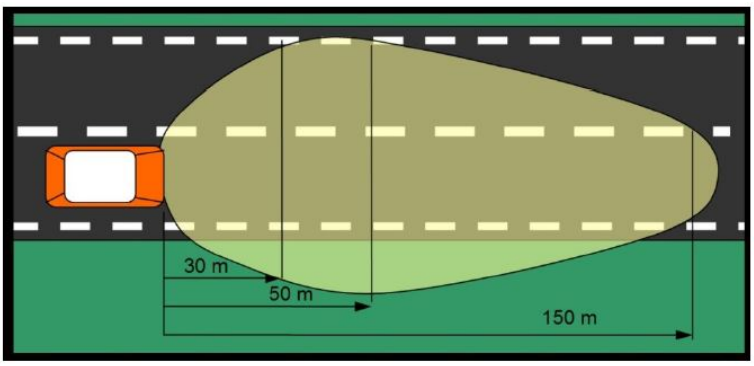


Figure 2.7: High beam, top view

Figure 2.8: High beam, light projection on road

2.6 Advanced low beam patterns

Considering the evolution of headlamps some other low beam patterns were developed in order to give the right illumination in different situations. At this point will be given only a short description of main different patterns developed and commercialized, in the next chapter will be explained how these patterns are realized. The following 6 main low beam patterns have been developed (see figure 2.9):

- Country Light, basic beam pattern with cornering lights off.
- Town light, country Light with cornering lights dimmed down to 20% intensity (increased beam spread at low speeds).
- Cornering light, full intensity with turn on or steering wheel turned. Also used as static bending light with curve radusi up to 500 meters.
- Maneuvering Light, both cornering lights and back-up lights on.
- Stop mode light, town light without cornering lights (reduced electrical power with engine off).
- Tourist mode, slightly reduced intensity and leveling moved slightly downward.

The EU regulation 123 refers to the approval of adaptive front lighting systems (AFS) for motor vehicles.

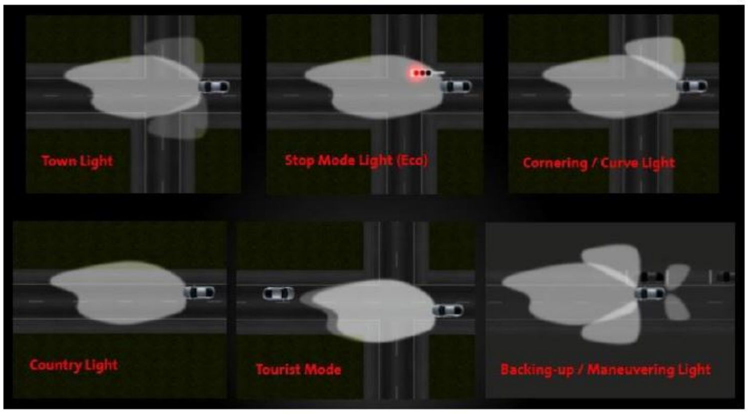


Figure 2.9: Low beam patterns, projection on road

2.7 Isolux diagrams

Isolux diagrams are very useful in order to compare the performances of headlamps, they also gives an idea of light distribution. In the figure 2.10 there is an example of isolux diagram. The light is projected on a screen and measurements of illumination expressed in [lm] are taken. Than a map of illumination is created in function of a reference system expressed in [deg]. The closed lines inside of the diagram represent areas with the same illumination in the YZ vehicle plane. Considering the closed lines is possible to have an idea of how the light distribution will be, in this case is just a rectangular distribution. The isolux diagram could be also without colors with just the closed lines. In the figures 2.11, 2.12, 2.13, 2.14 some examples of low-beam, high-beam isolux diagrams and also the photo of the light projection on the screen are represented. Sometimes diagrams could be expressed in candela [cd] instead of [lm] but the concept of diagram interpretation is the same. Another way of representation is by expressing the isolux diagram in XY vehicle plane, in the figure 2.15 and 2.16 there are some examples. These diagrams usually are called bird view since there is the representation from the top view of the vehicle.

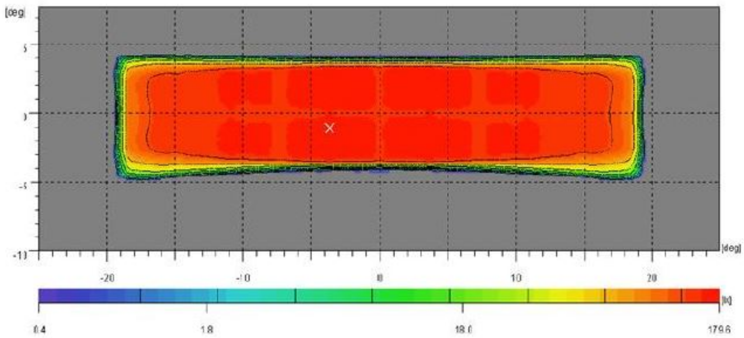


Figure 2.10: Isolux diagram example

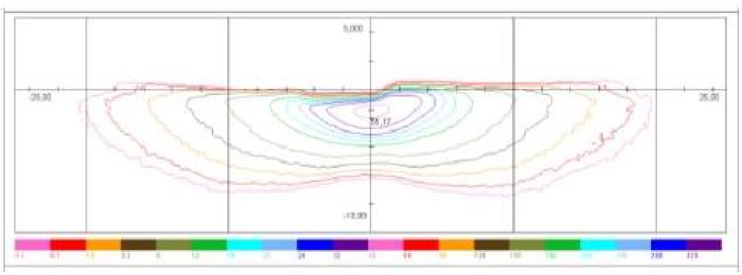


Figure 2.11: Isolux diagram, low beam function

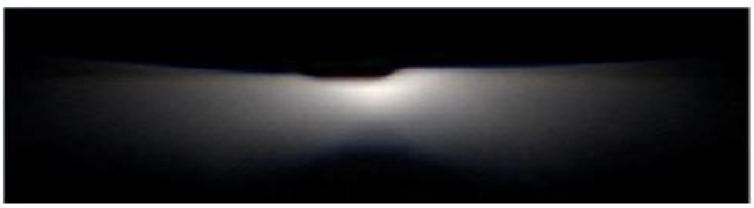


Figure 2.12: Low beam function, projection on screen

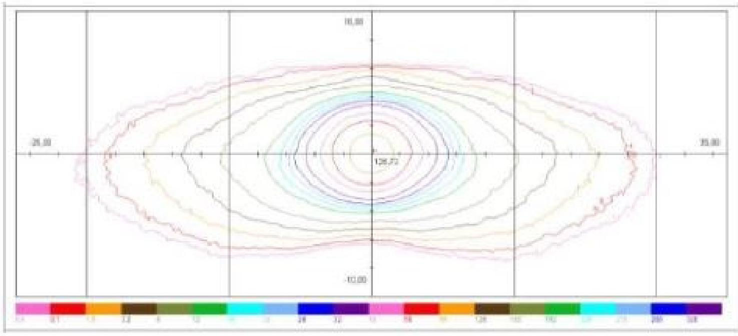


Figure 2.13: Isolux digram, high beam function,

Figure 2.14: High beam function, projection on screen

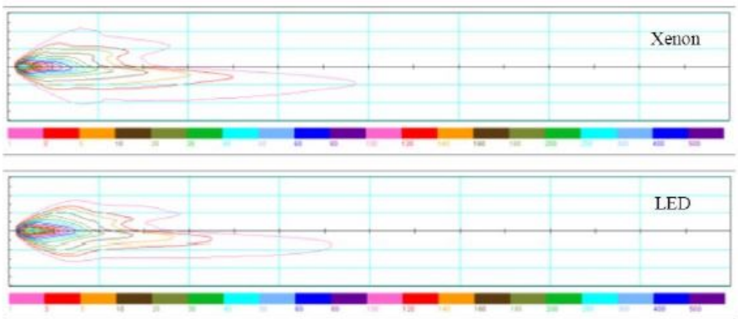


Figure 2.15: Bird view of low beam function

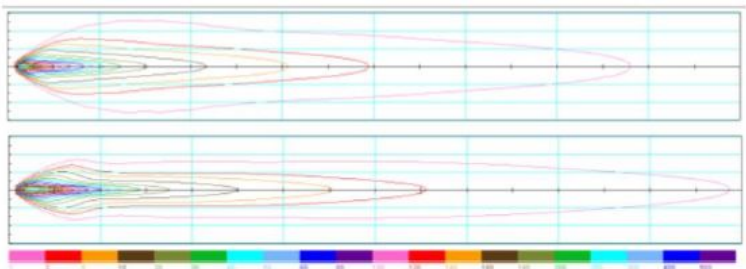


Figure 2.16: Bird view of low beam function

2.8 Goniophotometer

A Goniophotometer is a device used for measurement of the light emitted from an object at different angles. The device could be the headlamp a module or a light source mounted on a support, the light is projected on a screen at a certain distance and the measurements are taken. The goniophotometer is composed of the following parts:

- Mounting structure, where the headlamp or other light sourced could be mounted. The mounting platform allows rotation around the three vehicle axis (Z,Y,X) see figure 2.17.

- Control and elaboration module. The rotations of the platform are controlled, the data acquired are visualized and report are produced. The headlamp functions are also controlled.
- Power rack, contains the power supply unit for the headlamp and is controlled through the control module.
- Projection screen, where the light is projected to take the measurements.
- Light sensor, placed in the middle of the sceen trasmit the mesurements to the elaboration unit, see figure 2.18.

Figure 2.17: Goniophotometer mounting structure

Figure 2.18: Goniophotomer light sensor and protection tube

2.9 Lighting simulation vs. on road and laboratory test [1]

Photorealistic visualization is state of the art in exterior lighting development with known benefits, so visualization tools like Lucid Drive (Synopsys) enable light assessment early in the development process and gives a realistic first impression of headlamp performance on the road. Especially the general impression and the homogeneity of light distribution on the road are evaluated by photometric and realistic visualization. The question arises how good the visualization corresponds with the visual assessment on the road and finally can the night evaluation on the road really be eliminated, especially if optical mock-ups are used in early development phase. This section presents a correlation analysis of photorealistic visualization and real road assessment of the different beam pattern. Of course Lucid Drive is a dynamic benchmark and usually used to test AFS functionality and assessment of beam pattern is commonly done with Isolux data, but here is the initial question: to what extent is possible to trust on beam pattern visualization or in other words how good correlates the visual appraisal on the road with the virtual displaying, when focusing on the main criteria seeing distance, spread, homogeneity and brightnes? A test were conducted for this purpose, seven different headlamp sets, reflector and projector lamps, was chosen whereby importance was attached on strong differences of optical characteristic. The same lamp sets were showed to the test subjects firstly real on the road and secondly virtual on a wide screen based on photometric measurement. The procedure was done within 3 days. In order to avoid disturbance the road conditions on test track and in visualization should be as equal as possible. Therefore a static evaluation without moving vehicles under standardized conditions were performed so principally the selected headlamps mounted in same height and gap, on the road with help of a special test facility. The actual test track was recreated in Lucid Drive and comes very close to this (see Figure 2.19 and 2.20). Also the operating voltage on real lamps was 13.2 V same as nominal test voltage for measurement, however of course not calibrated on luminous flux. The test subjects, overall 18 people with and without automotive lighting experience, got a questionnaire where they had to appraise the beam pattern in a ranking scale of 1 (extreme poor) to 10 (excellent). The following fourteen criteria were asked to assess the beam pattern characteristic on the road and on screen with a short definition and description:

1. Low Beam – seeing distance left side (driver side)
2. Low Beam – width left side up to 50 m
3. Low Beam – width right side up to 50 m
4. Low Beam – seeing distance right side (passenger side)
5. Low Beam – harmonization between near and far zone
6. Low Beam – homogeneity
7. Low Beam – brightness
8. Low Beam – width up to 10m left and right side
9. High Beam – width left side up to 90m

10. High Beam – width right side up to 90m
11. High Beam – seeing distance (center of the road)
12. High Beam – homogeneity
13. High Beam – brightness
14. High Beam – harmonization to the low beam

Here it should be pointed out the analysis shall not judge strengths and weaknesses of used headlamp sets, although the beam pattern have been appraised. Rather the examination shall prove that different beam pattern characteristic will be recognized by appraisal on the road and on screen in same way. The real road scene is on a straight test track, approximate by 150 m long and ends with a mound. The middle of the road was selected as the viewing position to enable a better spread evaluation due to the limited right side distance. Left and right side on road were located gray charts every 10 meters as distance markers for seeing distance assessment. These objects approximate 40 cm x 40 cm with an 80% reflective gray. The lamps were presented with help of a test facility which can be switched on one by one with a short break and the test subjects positioned behind this.

Figure 2.19: Real illumination on road

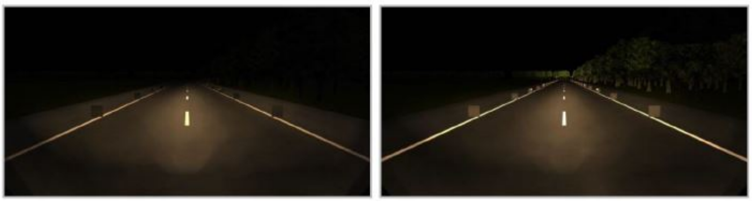


Figure 2.20: Simulation of road illumination

As mentioned before the real test track has been simulated in Lucid Drive Road Editor and comes very close to this, also with 80% reflective test charts every 10 m distance with trees on the right side and green on the left side. This scene was presented to the test subjects on a high resolution wide screen of approximate by 6 m width and 3,5 m height and in 4 m distance. This enables coverage of viewing field as good as possible. Of course the screen is sRGB and Gamma curve calibrated, but not optimized for Lucid Drive. It should be mentioned here, that the image projection is done by a beamer system on the rear side of the satin- transparent screen. This created a strong vignetting of 2:1 to the border of the screen. Even through the outer scene area is affected, it can be assumed the area where have been evaluated the beam pattern are in the inner circle.

The visual properties was set after a pre-evaluation with:

1. fixed maximum Luminance on screen maximum Luminance 120cd/m^2
2. BDRF type: default
3. Map function: Munsell
4. Ambient light: 0,5 cd/m^2

Based on the assessment by all 18 test persons was calculated the average rating of each lamp set with regard to each criterion and finally this result was converted in a ranking, 1. "best" heading and 7. "worse" headlight in this criterion. This ranking was used for statistical analysis too, therefore the correlation coefficient is Spearman's rank correlation which also make sense, because the rating scale from 1 to 10 is not linear scaled equidistant. As mentioned in the beginning, this examination should not assess the quality of beam pattern, even if there is a ranking result. Rather this rating is argument for distinctness, how strong can be recognized differences on the visualization screen and how strong the correlation to real road assessment is. The figure 2.21 shows the correlation and level of significance of each criterion.

	Criteria	Spearman Correlation	p-Value	Interpretation Correlation	Interpretation p-Value
1	Low Beam – seeing distance left side	0,643	0,119	moderate	not significant
2	Low Beam – width left side up to 50 m	0,75	0,052	strong	significant
3	Low Beam – width right side up to 50m	0,721	0,068	strong	significant
4	Low Beam – seeing distance right side	0,214	0,068	no correlation	not significant
5	Low Beam – harmonization between near and far zone	0,786	0,036	strong	significant
6	Low Beam – homogeneity	0,767	0,044	strong	significant
7	Low Beam – brightness	0,775	0,041	strong	significant
8	Low Beam – width up to 10m left and right side	0,964	0,001	very strong	significant
9	High Beam – width left side up to 90m	0,893	0,007	very strong	significant
10	High Beam – width right side up to 90m	0,714	0,071	strong	significant
11	High Beam – seeing distance	0,607	0,148	weak correlation	not significant
12	High Beam – homogeneity	0,636	0,124	moderate	not significant
13	High Beam – brightness	0,857	0,014	strong	significant
14	High Beam – harmonization to the low beam	0,883	0,008	very strong	significant

Figure 2.21: Correlation and level of significance of each criterion

Altogether the comparison between the visual assessment on the road and virtual visualization on screen shows strong correlation with statistically significance of the most criterions but four criterions failed the statistical acceptance and don't correlate. It is remarkable that all seeing distance assessments are affected and required a detailed consideration with the question why this might be. Why the criterion 12. "Homogeneity High Beam" is not significant can't really explained. Firstly because the point 6. "Homogeneity Low Beam" is significant in this study, secondly the experience with simulation tools like Lucid Drive shows that "Homogeneity" is visualizable and assessable pretty well. Substantial difference of seeing distance to all other visual assessments is the strongly dependence on Luminance threshold and therefore the contrast ratio on the road. Hence it is helpful to investigate the Luminance on the road scene and the contrast between gray test charts which were used as distance markers. Of course, following analysis based on Luminance images by one headlamp set only. The Luminance images (see Figure 2.22) depict the differences between real road and simulation. The maximum Luminance on the road is approximate 1:6 less than on the screen, in this sample 2,25 cd/m^2 on the road and 13,38 cd/m^2 on the screen. This could be an issue regarding mesopic vision because commonly 10 cd/m^2 Luminance is described as adaption border and the visual perception would switch to photopic, definitely these result in different recognition. On the other hand the average Luminance of the road scene on screen is less than 4,6 cd/m^2 which is commonly taken as adaption level, consequently this issue can be excluded.

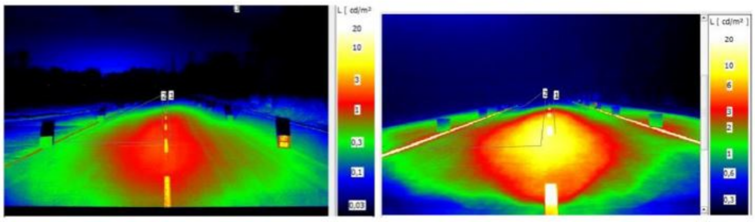


Figure 2.22: Luminance real vs simulation

Next consideration is the Luminance level relative to distance on the road. A gray-scale section road along the middle lane was created in Luminance image, starting with the 10 m mark until end of the road, see measure zone 1 in Luminance images (see Figure 2.22). Nevertheless, in conclusion there is no better approach to the low gradient of Luminance on the real road, the model curves decrease much stronger than on the road measurement. Most likely this is the reason why seeing distance can't recognize as similar as on the real road. All in all we can conclude there is a good correlation between the assessment on the road and the photorealistic visualization by Lucid Drive based on lamp measurement regarding the criterions width, homogeneity and brightness. The criterion "seeing distance" has to be excluded and didn't show a significant correlation. Of course, therefore is still the Isolux on the road assessment the right method. The highly properly reason for this issue is the Luminance decreasing along the road. While the light distribution on the real road is constant less decreasing, the decreasing of Luminance in visualization with BDRF function is much stronger. This results in a poorly to be evaluated zone near of cut-off line. The visual effect is that the beam pattern in visualization break off, where light is perceptible on the real road, however with Luminance less than 0,05cd/m^2.

2.10 LUXEON Neo LED [2]

In this section, the LUXEON Neo LED will be presented based on Wafer Level Packaging (WLP), which provides high-contrast, small light emitting area (LEA) at competitive flux levels, high-packing density and high thermal efficiency. LUXEON Neo comes in two different chip sizes of 0.5 mmm^2 and 1.0 mmm^2 enabling flexibility in the optical layout, the number and size of segments and the overall light source dimensions. Hence LUXEON Neo is well suited for dynamic headlamp functionalities such as a Matrix light. In other applications such as a reflector-based distributed low beam, the small and high contrast light emitting areas are used to design very slim headlamps. Based on the LUXEON Neo a low beam with multiple individual cavities of only 20 mm height each, can be demonstrated. Lighting is an increasingly important innovation driver in the automotive market. The different lighting functions are used not only as differentiators among car makers but also used to create a unique brand images. In automotive head-lighting functions two trends are fast emerging: increased functionality and new styling. Some of the latest innovations coming to market are the adaptive driving beam or the glare free high beam. Such lighting solutions are based on vision systems with light distribution based on individual switchable light segments also called matrix beam. This function offers maximum illumination of the environment ahead and blacks out specific areas to prevent glare onto the oncoming traffic. Also the importance of automotive headlight styling has increased dramatically in the past few years. Modern headlamp designs include multiple cavity reflectors and projection architectures. A general trend is to create slimmer and smaller optics for the main light functions to achieve a sportier look and provide additional space for other functions such as the DRL and position lights. All these trends demand increased performance and design flexibility of the light source. A dynamic switchable beam distribution is based on individual addressable light areas with high flux and resolution. Headlamps with small optics require LEDs with high luminance, high contrast, good positioning tolerance and excellent thermal performance. WLP based LEDs are able to address all the application needs of future automotive LED head lighting trends mentioned above. Chip Scale Packages (CSPs) based on Wafer Level Packaging (WLP) principles are novel to the LED industry but they are the mainstay of the semiconductor industry. Development of WLP in Si ICs (available since the turn of the millennium) was driven by miniaturization, improved thermals, higher reliability, and the need to connect to an ever increasing pin count on an ever shrinking chip. WLPs allowed for ease of integration into Level 2 (L2) packaging; die level processes are moved to wafer level thereby allowing for a higher level of integration into one device or chip. It is therefore a natural evolution for such packaging innovation to proliferate into other industries including the LED product space. CSPs are traditionally defined as fully functional packages that are of equal size or slightly larger than the actual size of the chip, in this case the active area of the LED. CSPs are surface mount devices (SMD) that do not require an additional substrate or interposer and can be attached directly to L2 electronic boards using standard assembly packaging equipment. LUXEON Neo is a WLP based single chip emitter with contact redistribution within the chip so that N and P contacts can be direct solder (SAC or AuSn) attached onto L2 boards without interposers or sub-mounts (See Figures 23 and 24 for schematic). Currently, LUXEON Neo is offered in two chip sizes: $1mm^2$ and $0.5mm^2$. The maximum outer dimensions for the 1 mm^2 and 0.5 mm^2 emitters are 1.5x1.5 mm^2 and 1.2x1.2 mm^2 respectively.

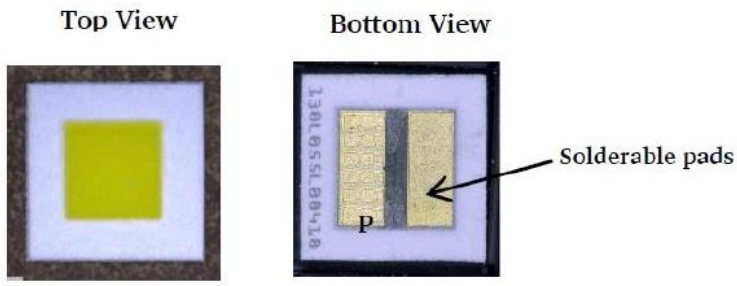


Figure 2.23: LUXEON neo LED

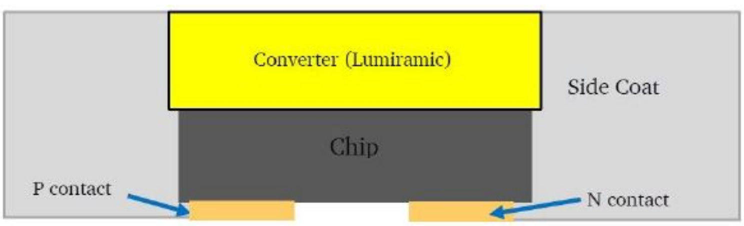


Figure 2.24: LUXEON neo LED, lateral view

One of the key advantages of LUXEON Neo is that it has the growth substrate (sapphire) intact which provides mechanical and thermal robustness and enables a good optical bond to the converter (Lumiramic). Being a homogenous ceramic, Lumiramic is very robust and can survive very high temperatures without damage. Furthermore, it has the highest thermal conductivity of any of the common converter architectures, including phosphor in glass. The combination of high efficiency, robustness and low thermal resistances makes LUXEON Neo (WLP with Lumiramic converters) an ideal product for high luminance emitters. The WLP chip has an embedded Transient-Voltage-Suppression diode (TVS) for ESD protection of up to 8kV HBM, which offers customers the flexibility and simplicity of attaching the WLPs without an additional TVS on the L2 board. As shown in Figure 2.25, with LUXEON Neo, one level of interconnection can be completely eliminated resulting in significant improvements in thermal and positional tolerance budgets.

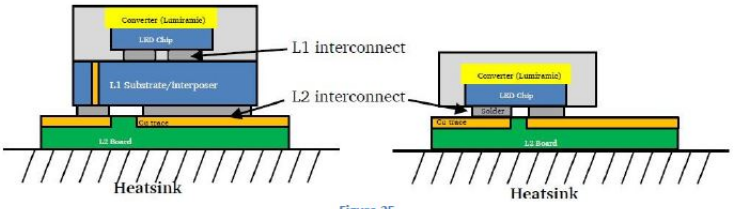


Figure 2.25: LUXEON neo LED improvement

WLP-based LUXEON Neo has demonstrated emitting 600lm at greater than 70lm/W from a 1.1mm^2 light emitting area, at 2.5A DC, with a junction temperature of 100C – see Figure 2.26. With LUXEON Neo this performance is scalable, either by changing the chip size, or by bringing multiple emitters together in one light-source, for instance by making m x narrays.

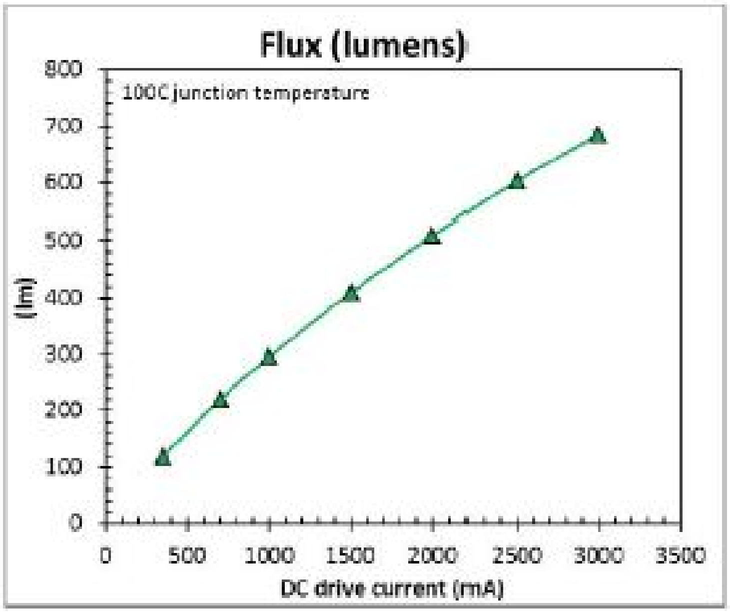


Figure 2.26: LUXEON neo LED performance

The luminance of LED-based automotive light-sources will improve substantially as the efficiencies of the base technologies improve and the maximum power density of the devices increase. In particular, the chip and package must be designed to handle up to 20W/mm^2 of power and the semiconductor growth technologies must be optimized for very high power operation. With these efficiency improvements and higher drive capabilities in place, a single 1mm^2 WLP chip is expected to produce more than 900lm (>250Mnits) at a current of 3A, or more than 1200lm (>350Mnits) at a current of 5A. By changing the chip size and drive current, the flux values can be scaled to one quarter of this value up to twice the value, all while maintaining the same luminance and power density. Due to its small footprint, LUXEON Neo is ideal for matrix applications. In principle any m x n matrix configuration can be realized, of course with increasing complexity of board layout and driver electronic for high pixel numbers. The minimum emitter to emitter spacing depends on the board and placement tolerances as well as electrical routing and thermal design. Figure 2.27 shows a matrix board design with 3x28 LUXEON Neo 0.5 mm^2 that can be realized on a single-layer metal core printed circuit board (MCPCB). It demonstrates the feasibility of implementing an LED array on a single layer PCB with minimal LED pitch and sufficient thermal performance for head lighting application. The matrix setup consists of multiple blocks for sub-segmentation of the high number of LEDs needed for matrix application. In each block, the LEDs are connected in series with mid contacts for single addressability. The parameters determining the minimum pitch between the LEDs in this arrangement are the number of copper tracks between two blocks running to the periphery of the board, the copper track width, and the copper clearance. To ensure that a current carrying capacity of 500 mA is maintained at 85°C ambient temperature and an allowed temperature rise of 20°C, the chosen copper track width is 0.2 mm assuming a layer thickness of 35 μm. The copper clearance is chosen to be 0.2 mm, resulting in a minimal LED pitch of 2.5 mm for the given conditions. The dimension of the matrix array is about 70 mm x 10 mm. The thermal performance of the assembly is a critical aspect to be considered when designing LED matrices.

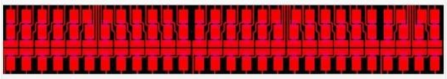


Figure 2.27: PCB chip with luxeon NEO

Close spacing of LEDs has two drawbacks from thermal performance perspective. First, the top Cu metallization, which serves as a heat spreader is limited on a per LED basis. Second, thermal crosstalk between LEDs can occur. These two factors increase the thermal resistance compared to an individual LED on a board and are determined by the pitch between the LEDs. As an example, the thermal performance of the matrix assembly is evaluated using finite-element simulations of a 3x4 LED array of LUXEON Neo 0.5 mm^2 on a 1-mm-thick Cu-MCPCB of dimensions 40 mm x 40 mm. The spacing of the LEDs is 2.5 mm in both x- and y-direction. The board is mounted on a plate Al heat sink using 50 μm thermal interface material (TIM) and the temperature at the bottom of the heat sink is set to 85°C. The temperature distribution of the LED array arising for 1.1W thermal input power per LED is shown in Figure 2.28. The observed temperatures are rather homogeneous. The hottest LEDs are those in the center of the upper row due to the slightly asymmetric pad design on the board. The largest difference in junction temperatures between individual LEDs is 1.8°C, indicating that the crosstalk between the LEDs is low for the given design. The thermal resistance Rth,jb of the LED and board assembly can be calculated from the junction temperatures and the maximum temperature on the underside of the board. If all LEDs are switched on, the maximum thermal resistance of a single LED to board underside is Rth,jb = 21 K/W (based on thermal power). For a typical application in a head lamp allowing a case temperature of 125°C (corresponding to a junction temperature of approximately 131°C), this results in a board temperature of 108°C assuming an LED drive current of 500 mA (corresponding to 1.1 W thermal power per individual LED).

This is well above typical head lamp ambient temperatures (e.g. 85°C), enabling this kind of matrix arrangement to be integrated in real head lamp applications.

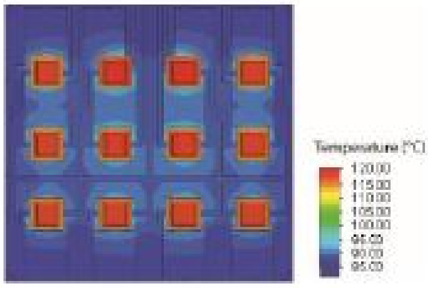


Figure 2.28: LED thermography

The typical target positioning tolerance for matrix applications is better than 50 μm (5 sigma) using standard surface mount technology reflow process. This tolerance basically is defined by the tolerance of the LED itself, the accuracy of the assembly process (including self-alignment) as well as tolerances of the board. Typically tolerance for light emitting area to solder pad center for conventionally packaged LEDs is larger than 50μm. With LUXEON Neo, superior alignment can be realized due to the very small LEA to solder pad tolerance of 25 μm which is an intrinsic benefit of the wafer-level fabrication process. The small mechanical tolerances of WLP LEDs are therefore a key enabler to achieve a total tolerance better than 50μm. However also the self alignment of the LED in the soldering process is a major contributor to the overall tolerances. For a metal defined footprint/board layout self alignment processes are less dominating the final device position than for solder mask defined layouts where the final position will essentially be defined via self alignment processes. Therefore, to achieve the target of 50μm total tolerance, careful the board quality is important and the alignment of solder mask and board metal layer needs to be well controlled. In principle, LUXEON Neo can be placed on Al- and Cu-based insulated metal substrate boards (IMS) as well as FR4 with thermal vias. For matrix applications, in general a board with a high thermal conductivity is important. A thick top layer copper (e.g. 70 μm) should be considered to improve the thermal spreading. LUXEON Neo can be solder-attached using typical Sn-based materials like SAC305. A stronger solder material like Innolot can be used to further improve the reliability under thermal cycling conditions. Already, the void level is within an acceptable range in a typical reflow process. Vacuum soldering can be used to eliminate most of the residual voids and helps to improve the thermal performance and position accuracy especially in z direction. A good balance between solder mask and bondline thickness can be used to reduce tilting of the LUXEON Neo. It is possible to demonstrate tilting tolerance (5 sigma) of 3° / 6° (normal to pad direction / along the pad direction) using a standard reflow process. In many typical matrix applications not all pixels need the same brightness. Full brightness is often only required for the center pixel, while the outer pixels often need less than 50%. As a consequence either the flux per pixel or the size of the pixel needs to be adapted. Using the combination of LEDs with different emitter sizes on one board the system costs can be optimized. Figure 2.29 show an example of an LED configuration for an adaptive High Beam application. When each LED will be placed below an individual pre-collimating optic, a very natural beam dynamic can be realized for these configurations. In conjunction with the mix-and-match nature of these emitter layouts, it is important to select a driver topology that enables different drive current for the different types of LEDs.

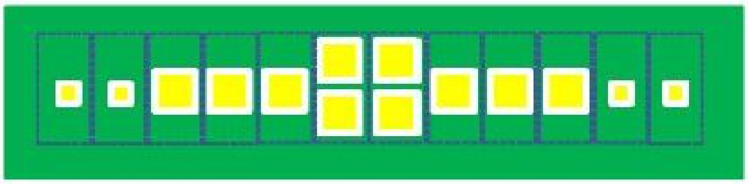


Figure 2.29: LED pcb for adaptive high beam application

The small footprint of WLP devices will enable the direct combination of driver electronic on board. Especially for matrix applications the interaction for switching electronic seems to be very relevant to reduce the complexity of interconnect. But also additional ESD protection can be integrated. Additionally optical sensors can be closely placed to the LEDs. The integration of primary optics on board level is key for many matrix concepts. Here the LED is placed closely to the entrance of an precollimation optics. The tolerance in Z height define the nominal gap between collimator entrance and light source. WLP devices show a significant advantage compared to LED packages with L1 interposers, because of the reduced tolerance in height. For LUXEON Neo the z tolerance can be as low as 25μm. WLP in HB / LB applications – smaller headlamp optics The ability of closed spaced customized LED groups will enable a wide field of new optimized LB source assembly's with improved design freedom as well as higher System performance. Figure 2.30 shows a sample configuration that can be used for an improved LB source that enables the optical system to bring more light close to the cut-off and reduce the amount of light in the for field close to the car. Alternatively this could be used as a bi functional HB/LB source.

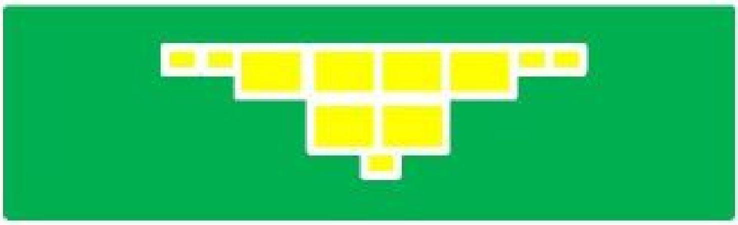


Figure 2.30: LED pcb for improved low beam application

Especially the ability to realize high luminance in combination small light emitting area can enable a significant size reduction of the optical system. While the minimum height of headlamp optics today is somewhere between 2.5 cm and 3 cm an 0.5 mm^2 LUXEON Neo can bring it down to less than 1.6 cm. Figure 2.31 show an example design of an LB reflector based on an 0.5 mm^2 LUXEON Neo source in comparison to an design based on an 1 mm^2 LUXEON Neo. In both cases the hot spot size in vertical direction is about 2.5° (FWHM). This can be considered as the acceptable limit. But for the 1 mm^2 source the reflector is about 50% higher. Depending on the source luminance between 8 and 3 of these units will be needed to generate a low beam.

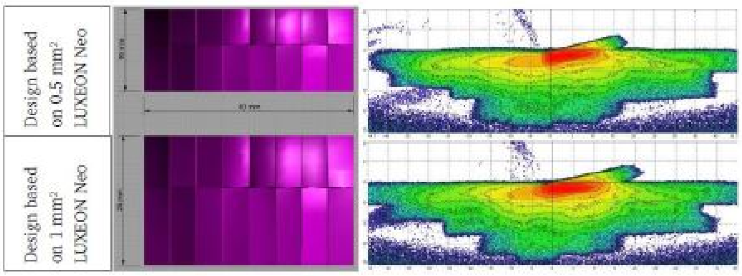


Figure 2.31: Reflector design depennds on LED dimensions

2.11 Luminous flux and homologation standards [3]

Within many years the progress in halogen headlamp design lead to much better road illumination than primarily required by UN ECE Regulation. This is result mostly of improved efficiency of optical headlamp design. However it is still much less than 100%. LED technology connected with modern optics allow for much higher efficiency just close to 100%. Therefore it is possible to obtain road illumination comparable to halogen headlamps in LED headlamps by much smaller luminous flux than presently utilized in halogen headlamps. It is important because of energy efficiency, design and cost restrictions. But for LED headlamps it is required 1000lm luminous flux as additional guarantee for performance. From one side it significantly restricts LED headlamps progress but from the other the remove of flux requirement can lead to very poor road illumination. This is because of historical reasons concerning way of defining requirements in all headlight regulations. This more general problem is because all present type approval requirements are based on old paraboloidal design and vertical screen illumination idea. Fixed flux is the etalon bulbs for type approval tests supplement this outdated idea. Flux requirement is not appropriate from performance and safety point of view and should be replaced by more objective criteria. In section is presented analysis of present situation. Simple and effective original proposal is presented to modify obsolete headlamps type approval requirements. It could help to obtain the road illumination caused by LED headlamps comparable to good present halogen headlamps without flux restrictions. Present minimum ECE type approval requirements for halogen passing beam headlamps reflect very basic road illumination. It is described by values defined at the vertical screen surface (Fig.2.5) Additionally light source used in headlamp should meet requirements described in appropriate regulation. LED headlamps for today do not use standardized exchangeable light source but only LED light module(s). Because of that it is additionally required for LED light module minimum luminous flux of 1000 lm. For halogen headlamps design of the headlamp is more or less similar for different headlamps. Basically it consist of reflector, in the past paraboloidal one, or ellipsoidal with filament placed close to the focal point. Similar rule exist for HID arc. As the classic light source emit light nearly in the sphere around filament or gas discharge arc this kind of design allow for effective use up to around 50% of luminous flux. Even though to satisfy minimum requirements of regulation it is enough to use a small part of this value. Fig.2.32. shows recalculation from measuring screen values (Fig.2.5) to the vertical illumination at the road surface with rounded lux values.

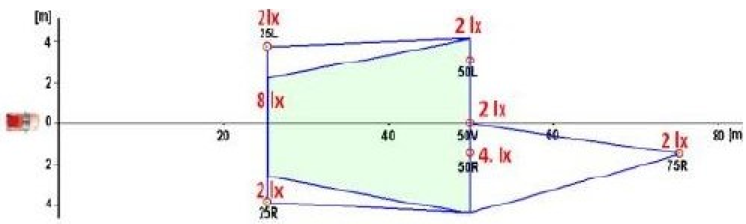


Figure 2.32: Recalculation from measuring screen values

Values of illumination at the road surface (mostly expressed as isolux lines) are widely used from many years to asses quality of headlamp and road illumination. By this representation it is possible to have more detailed information of quality of illumination e.g. in the terms of range and width. There are also used vertical illumination values to determine potential possibility to see object on road. Most popular are isolux line of 3lx, 1lx and sometimes other values. In Fig. 2.33 are shown examples of isolux lines of road illumination for real contemporary halogen headlamps used as examples to prepare CIE assessment method for vehicle headlighting system. It is easy to see that real halogen headlamps allow for much better road illumination than minimum requirements.

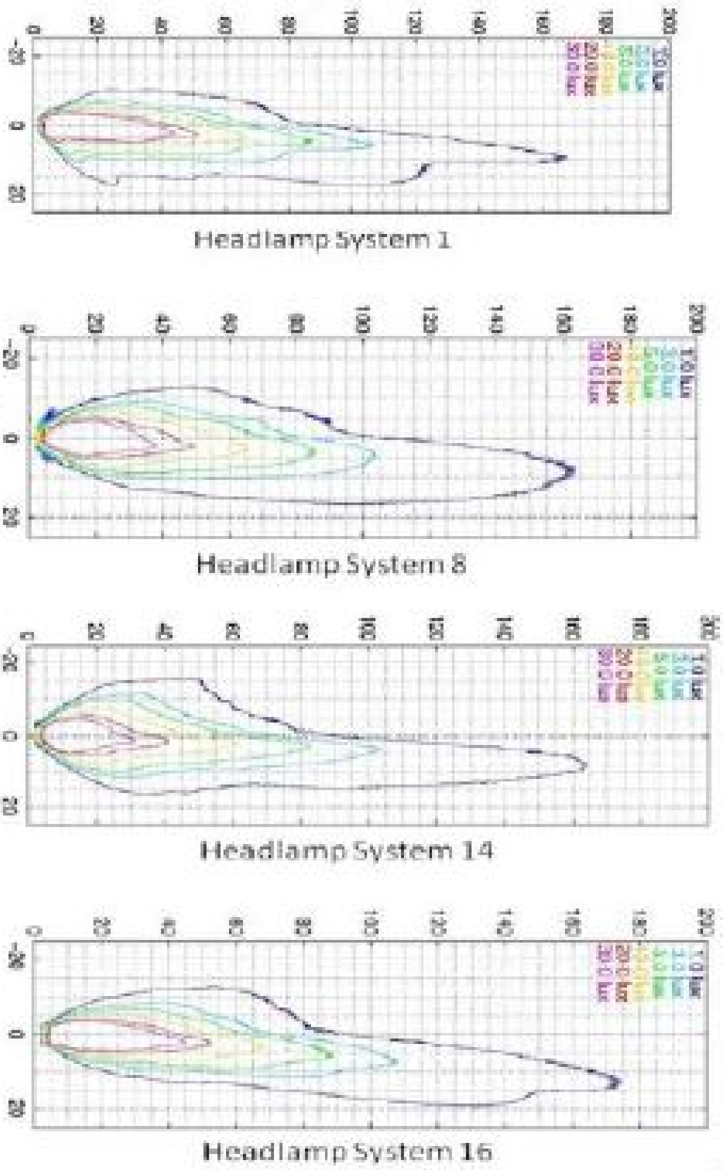


Figure 2.33: Isolux lines from halogen headlamps

To have more adequate imagination in Fig 2.34. is presented approximated area covered by present requirements but distances are the same as for isolux line plots of presented halogen headlamps. The meaning of this comparison is clear: Type approval requirements are very basic and headlights meeting only such requirements should not to be recommend for general use. The real halogen headlamps which illuminates the road much better than such minimum have not unique designs are not very expensive. Of course on vehicles are used also HID headlamps with luminous flux up to 3000 lm which allow for adequately significantly better road illumination than best halogen headlamps.

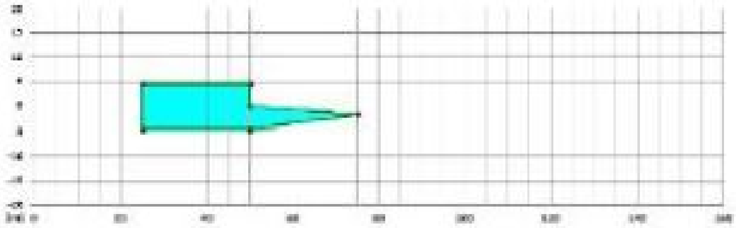


Figure 2.34: Illumination requirements from homologation standarts

LED headlamps light distribution can be much easily optimized because of small light emitting area of LED. It is also possible to use multiunit headlamps. Laser headlamp light sources (in fact LED modification) are even smaller with higher luminance and give additional freedom for designers. Is possible to use any present headlamp construction as base for optical design of LED headlamp. It is only needed to consider hemisphere light emission. It is also possible to utilize many modifications of well know design e.g. as top or bottom illuminated FF reflectors. Attractive possibility is to utilize only single plastic optical element with combined transparent FF lens and total internal reflection phenomenon which can allow for use nearly 100% efficiency of luminous flux emitted by LED. In such situation it is possible to obtain much better road illumination than done by best halogen headlamps under the same flux emitted from light source(s). From the other side when so effective optical design will be used it is possible to obtain "halogen comparable" road illumination by much lower luminous flux of LED light source. As was shown above to meet only minimum requirements of present "halogen based" regulation with effective LED headlamp it will be enough to use LED with only fraction of present 1000 lm flux. It is a strong temptation for headlamp manufacturers to reduce costs and simplify lamp design, cooling, power consumption etc. As result it is observed pressure to remove or reduce flux requirement for LED. From safety and performance point of view it should be also interest in offering better quality illumination by LED headlamps than today. Because of lack simple and clear comparison method for headlighting quality a base for general headlamps comparisons it is used light source category or design. It is assumed that each next fresh light source causes better quality of headlamp. LED's (or laser) are commonly judged as the best one. In fact it is not true because the most important factor is not only efficiency in the use of luminous flux but also light distribution in beam pattern. Final customer has no possibility to compare real quality of headlamp and usually believe in light source potential. In such situation reduction of flux for LED headlamps and rely only on minimum "halogen based" regulation can lead to LED headlamps quality much lower than present halogen headlamps using H4 bulb. In the meanwhile it is commercially advertised that LED headlamps as well as laser are the newest technology and guarantee even better road illumination than older one eg. HID. To have better imagination how present requirements are defined let us examine relationship between screen and road surface illumination. Lighting scheme is presented in Fig.2.35.

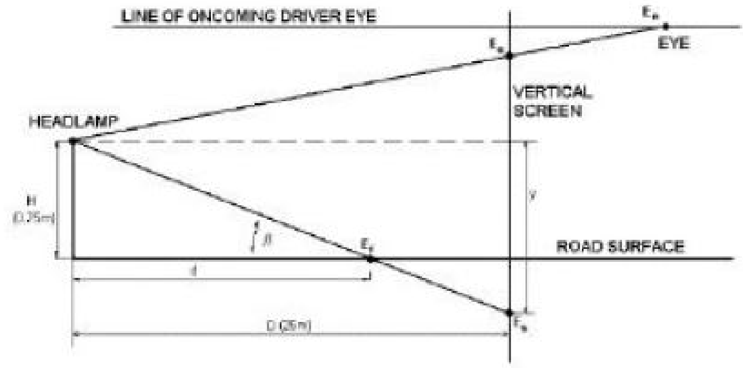


Figure 2.35: Calculation of road illumination

Vertical illumination Es is described by the formula
$E_s = E_r \cdot d_2 / D_2 = E_r \cdot d_2 / 625$ (1) Where: E_s - screen illumination in (lx), E_r – vertical road illumination in (lx), d - distance on the road in front of the vehicle in (m), D=25 m is nominal distance from headlamp to measuring screen. Vertical position on the screen y in (m) equivalent to road distance d can be calculated as: y = -H · D/d = -18.75/d (in m) (2) where H=0.75 m is nominal headlamp mounting height d. Plot of equation (2) is presented on Fig.2.36

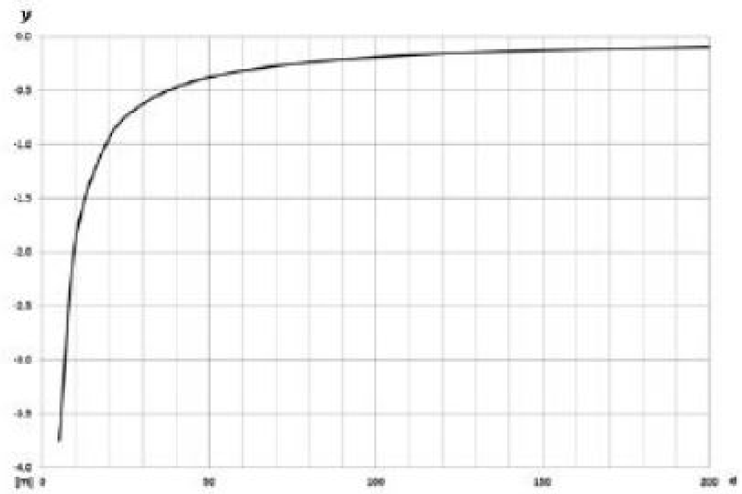


Figure 2.36: Plot of equation (2)

In Fig. 2.37. to 2.38. below are presented plots of relation between screen vertical position and screen illumination for the fixed road vertical illumination. Fig.2.37. represent screen illumination for uniform road surface vertical illumination for 5lx, Fig.2.38. for 1.5 lx and Fig.2.39. for 0.5 lx. These three values are chosen because they are commonly used for assessing road illumination in terms of range and width. For real road condition presented values are around two times bigger because there are two passing beam headlamps on the vehicle giving 1 lx, 3 lx and additionally 10 lx value.

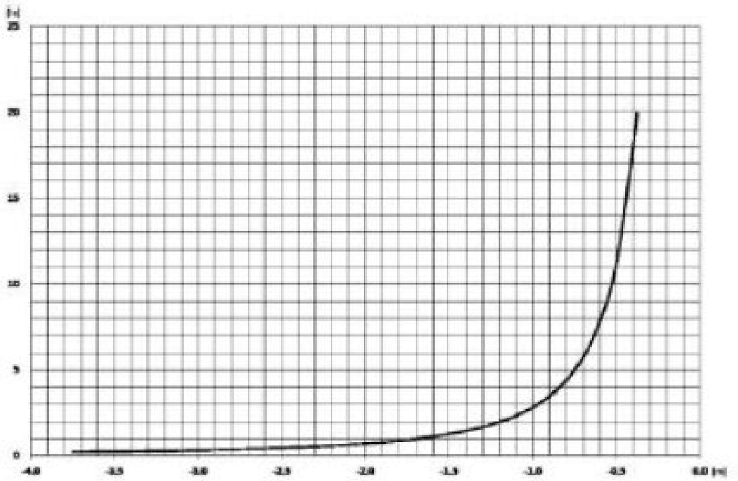


Figure 2.37: Screen illumination for uniform road surface, vertical illumination for 5lx

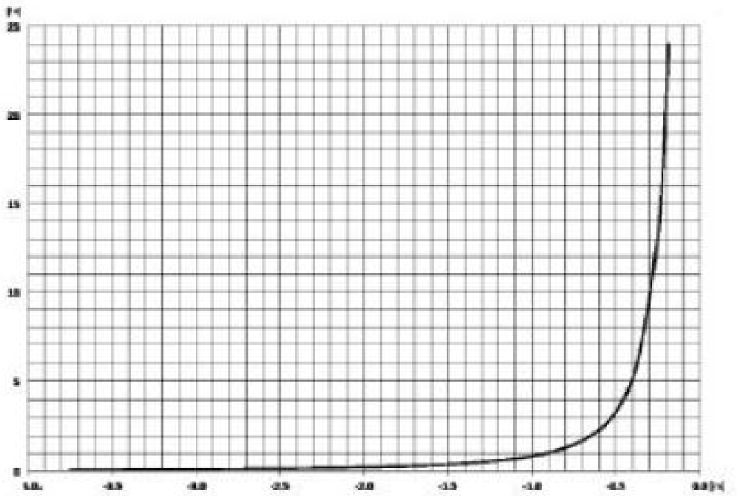


Figure 2.38: Screen illumination for uniform road surface, vertical illumination for 1.5lx

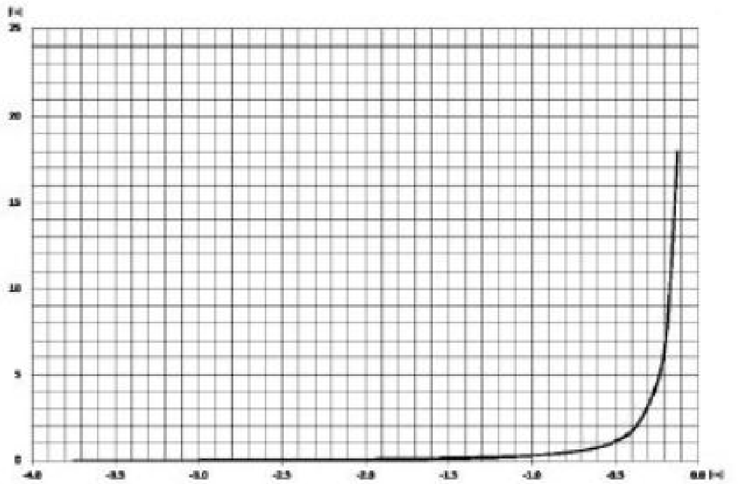


Figure 2.39: Screen illumination for uniform road surface, vertical illumination for 0.5lx

All above presented graphs are nonlinear. It explain why defining uniform illumination in zones at the screen is not appropriate to real road illumination quality. From the other hand reversing coordinate system from road to the screen is simple and this type of description can be very easy converted also to the photogoniometer angular system. Finally this method of defining type approval requirements do not cause any special difficulties by measurements. On the base of above analysis of theoretical backgrounds of road illumination and practical features of real halogen headlamps it was prepared alternative proposal of description type approval photometric requirements. Basically it is intended to simplify LED flux restriction problem. But generally it can serve to improve present inadequate way of defining passing beam requirements. The essence of the new proposal is defining areas in which minimum vertical illumination at the road surface is required. It is presented in Fig. 2.40.

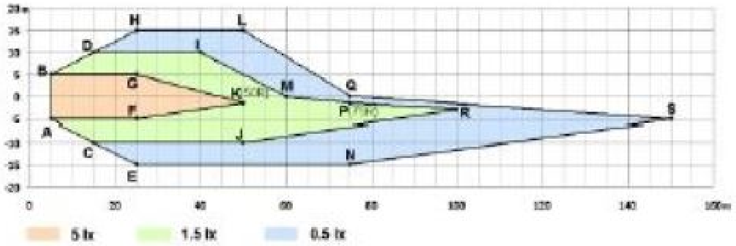


Figure 2.40: Definition of new proposal

When compare it with Fig. 2.32. representing present requirements it is easy to see that minimum required range will be increased 2 times and width 3 times regarding present minimum expectations. But in fact it is less than contemporary halogen state of art. When such values will be required there will be no more need to set any flux restrictions. Moreover it is realistic to obtain such illumination using light source staring from under 500 lumens and using effective optics design. It is not restricted to use more flux and obtain better road illumination, especially additionally illuminate areas according manufacturer or customer preference also exceeding present HID level. For laboratory measurements the required road values should be recalculated to the screen or photogoniometer coordinate system. The required laboratory photogoniometric measurements are very similar as today. The only difference is that in terms on angular coordinates the points of measurements will be not regular as a function of the angle. This way of defining requirements is completely independent on design. In fact it can be used not only for LED but for halogen or HID headlamps as well. It will define new quality – quality which practically exists in many contemporary halogen design but is neither defined nor required. This proposal is suggested to be optional one to preserve manufacturers freedom. If manufacturer do not want to follow it can follow present requirements but need to guarantee minimum flux of 1000 lm similarly to halogen light source. In this way will be no more discrimination of technology as well as ruthless flux requirement. The new proposed alternative to present ECE type approval photometric requirement is simple and allow for much better adjustments requirements to the safety needs. It allow to obtain by LED headlamps at least contemporary halogen performance. In addition it does not relate to luminous flux and allow to optimization LED headlamps design and efficiency. It should encourage manufacturers to concentrate rather on road illumination quality than meeting minimum values in measuring points. Proposal concern all technologies and is not connected to any of it neither direct nor indirect. As optional possibility it will not make strong pressure to follow it. But because of removing flux requirement it can be attractive alternative to develop optimal designs with high efficiency by minimum energy consumption and manufacturing costs. In the future it can be further developed to give alternative for present HID requirements as well as for adaptive headlighting standardization. In proposed philosophy it will be much easier prepare global technical regulation. It is because road illumination quality is more universal criterion and is less sensitive for national differences (American, European or other) than present systems defining values in angular coordinate system as true performance oriented.

2.12 Efficient usage of high current LEDs on ADB systems [4]

In this section will be showed the advantages of the integration of high current LEDs (HCLEDs) into automotive lighting modules, ranging from traditional mono or bi-function modules for the low and high beam functions, up to ADB modules. The objective is not to replace all the traditional LEDs by HCLEDs, but rather to use them at some specific positions to increase range, width as well as the beam overall performance. The main technological challenges to be solved are the higher thermal dissipation and bigger packaging, to determine the most efficient strategies to drive simultaneously different types of LEDs. The results were highly satisfactory to justify the integration of this kind of LEDs into our headlamp projects. Thanks to the introduction of LEDs, the automotive lighting technologies have evolved fast in the last two decades, giving raise to the modern ADB systems – Adaptive Driving Beam modules, with a high level of pixilation and automation. Besides the small packaging of LEDs, this lighting revolution, is also linked to the fast performance improvement of LED, for converting electric power into luminous flux (Fig. 43).

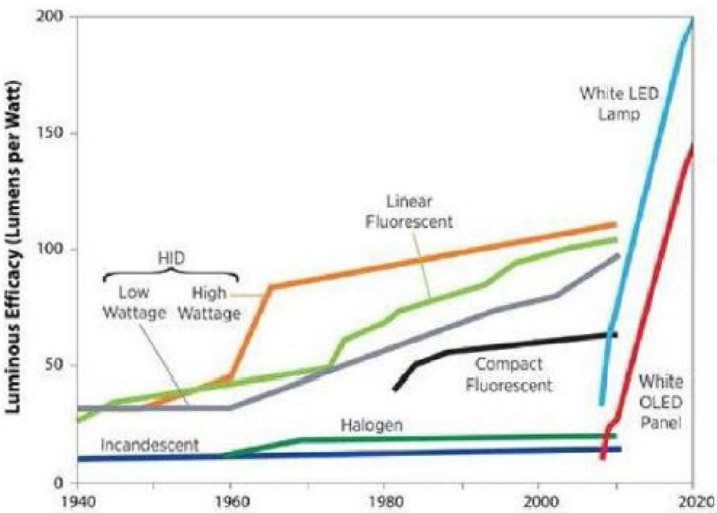


Figure 2.41: Energy efficiency comparison

From the lighting market today we can install modules using typically up to 5 LED emitting dices for functions as the low and high beams (standard or bi-function modules) or matrices of 84 or more LED dices for the most sophisticated pixel light modules. The performances can be modulated according to the number and disposition of LEDs, primary and secondary optical systems, and the association of different modules in super-imposition. Moreover, the so called 'high definition' headlamps associate high definition projection modules as additional elements, for an even higher resolution and symbol projection. Besides standard LEDs, we have also seen the introduction of laser diodes into automotive headlamps, integrated into high range high beam modules, for reaching ranges up to 500m, extending hugely the traditional high beam distributions. However, this technology introduces new challenges linked to the lower life time spam of laser diodes, laser security issues, speckles and high peaks of residual blue light.

Figure 2.42: Laser module for headlamps

The high range performance that can be obtained from laser diodes, comes from the high levels of brightness (flux density / emissive area) they provide in comparison to standard LEDs. In parallel to the arrival of automotive laser diode based sources, a new kind of LED has been developed – the so called “high brightness” or “high current LEDs”, providing much higher levels of brightness, closer to laser diodes, and keeping the good characteristics of standard LEDs: high life time, no laser leakage danger, and a much lower price. Different LED suppliers propose today HCLEDs, with well-defined roadmaps and validation process. The first optimized LEDs started with values of brightness around 130 Mcd/ m^2, reaching today 300 and targeting 400 Mcd/m^2 in the years to come (in comparison to laser diode 500 Mcd/m^2 typical brightness). The packaging of those LEDs started at $2mm^2$ to the present $1mm^2$, with perspectives of higher efficiency and lower power consumption. Despite the higher brightness levels, the first HCLEDs were less efficient (lumen/watt), producing more heat to be dissipated by the system, and requiring higher current levels (3 to 6 amps, compared to the 1-amp consumption for standard LEDs). However, the last versions of HCLEDs show a noticeable performance increase. The basic strategy of HCLEDs is founded in multiplication of current injection points inside of the emitting dices (Fig. 2.43).

Figure 2.43: HCLEDs package

Concerning safety issues, the evaluation of eye safety was done according to the standard IEC 62471: 2008 (”Photo biological safety of lamps and lamp systems”). Within the risk grouping system of this CIE standard, the HCLEDs fall into the class of Moderate risk (exposure time 0.25 s). Under real circumstances (for exposure time, eye pupils, observation distance), it is assumed that no endangerment to the eye exists from devices using them. As a matter of principle, however, it should be mentioned that intense light sources have a high secondary exposure potential due to their blinding effect. As is also true when viewing other bright light sources (e.g headlights). The design of the lighting modules must be adapted to avoid reduced output emission surfaces. Due to those interesting characteristics of the HCLEDs, and their potential to compete in particular to laser diodes technologies, at the PSA Groupe were performed an advanced engineering innovation program in order to evaluate how to best integrate HCLED indifferent configurations, i.e.:

1. Standard illumination modules: low and high beam individual modules, by replacing the standard LEDs by HCLEDs.

2. Bi-function modules (i.e. low/high beam), replacing some dices, to reach the bestcompromise between range, total flux, tolerable thermal effects. In the low beam, the main target functionality was a "boosted motorway function".

3. Other accessory modules (accessory high beams, fog lamps).

4. ADB – Adaptive Driving Beam modules, for matrix and pixel light functions. The replacement of some standard LEDs – namely the ones linked to the range, at the center of the high beam distribution).

5. Other future usages, for symbol projection associated to high resolution modules.

To fully test the integration issues, were modified and adapted serial modules integrating HCLEDs or designed variants, namely for ADB modules. The modified modules were further integrated into a mockup car or validated through simulation (optical and thermal simulations). The tolerance of standard optical surfaces were tested, designed for traditional LEDs, to HCLEDs, that have different parameters (focal point, image dimensions, flux, etc.). In some cases, the "old' surfaces could be kept, but in some configurations new optical designs had to be implemented (in particular primary optics lenses, that are typically placed at very short distances to the emissive diodes). In the last case, due to the higher brightness and heat emission, the material of the lenses must, in some situations, be revised. Among the developed prototypes, a physical mock-up of a bi-functional module with HCLEDs was integrated into the headlamps of a DS5 car (Fig. 2.44), used to perform field tests and to enable the parametrization of variants of standard lighting functions taking advantage of HCLEDs.

Figure 2.44: DS5 prototype with HCLEDs package

In parallel to the different above mentioned options of lighting beam improvement, were also investigated the potential of HCLEDs for the modules volume reduction and compactness, not described in this section. The lighting modules from different suppliers use a myriad of techniques to retrieve and redistribute the light flux from LEDs. The location of LEDs in the PCB depends of the light beam characteristics and impacts the design of reflectors and lenses inside the module. In Fig. 2.45 is presented a concrete example on how standard LEDs were replaced by HCLED versions to boost the low and the high beam functions:

1. Low beam PCB function using one 1mm2 HCLED
2. High beam PCB using one 2mm2 HCLED version (1x2 array)

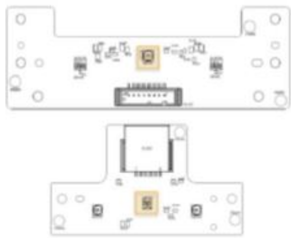


Figure 2.45: PCB of HCLEDs package

In the above configuration, is possible to evaluate, by simulation and by measurement, the thermal impact generated by HCLEDs towards the PCB and the surrounding standard LEDs, determine the correction to the optical sources, the eventual increase in the passive heat sink dimensions, or of an active fan air flow. For the level of performances obtained, the impacts were not relevant, and wasn't necessary to change the basic module structure (heat sink and PCB shape). In those configurations, the LEDs were relatively well distributed in the PCB. Conversely, for pixel light modules, the design of PCBs uses typically tightly arranged matrices or arrays of emitting dices, associated to matrices of primary optics lenses. In this case, the thermal and package issues play a bigger role, when some dices by bigger and hotter ones were replaced. Figure 2.46 illustrates one example of integration into a matrix beam module, where two LEDs were replaced by $1mm^2$ HCLEDs.

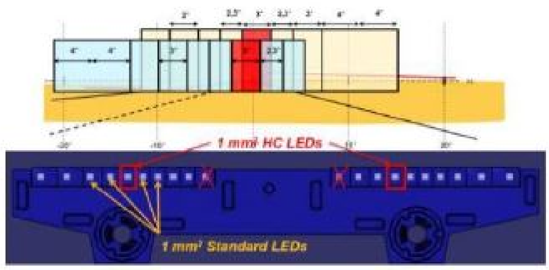


Figure 2.46: Matrix beam module with HCLEDs

The thermal analysis and simulations were performed on the PCB and it was optimized to fulfill the specifications. For other configurations, namely dense matrices of 84 LEDs, a further study must still be performed to determine the best possible thermal and electrical feed optimizations. In that case, the best option seems to be the creation of a sub-matrix of HCLEDs, slighted or completely separated from the one for standard LEDs. Besides the PCB optimization, the electrical driver must be compliant to higher current levels required for HCLED (between 3A and 6A). Depending on the driver supplier, different solutions are available / possible:

1. To add parallel 1.5A lines
2. To develop specific output lines with 3A or 6A

Fig. 2.47 illustrates one proposal of electronic driver, suitable for different applications

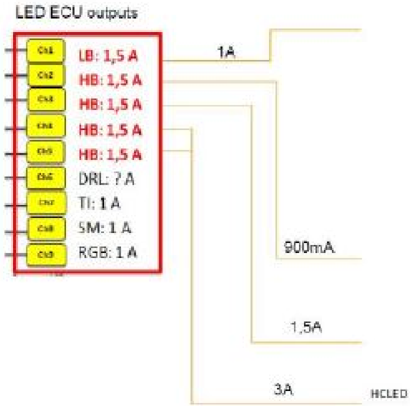


Figure 2.47: Electronic driver for HCLEDs

The thermal management of LEDs in function of the external temperatures must also be taken into account. For standard LED modules, was required a profile of flux stability against external temperature, up to a maximum temperature, from which the output flux is allowed to be reduced roughly linearly, in order to preserve the LEDs lifetime and other electrical functioning characteristics (de-rating procedure). The de-rating is controlled by the EE driver based on thermal sensing on the PCBs. The study with HCLEDs has shown that the same strategy can be applied in parallel, with no specific software or profiles to HCLEDs. As mentioned before, the impact of HCLEDs to optics comes from two main differences in comparison to standard LEDs:

1. bigger packaging

2. higher brightness and lower flux output

3. higher temperature close to the chip

The packaging options, in evolution nowadays depending on the HCLED supplier, and the bigger size chip, have an immediate consequence of creating a bigger image in the beam. In a matrix beam (or pixel light solution). The impact can represent from 0.5° to 1.5° of extra segment / pixel width. However, from some observations, the impact of extra width is not clearly seen when driving, and it is limited to the central zones of the beam pattern on ADB modules. The superimposition of half segments in the beam can also be adapted and optimized, and a special attention must be done to the eventual difference in contrast between the overlapping segments. In other configurations (with mono or bi-function modules), the reflector and optics can be optimized to take into account a bigger source size. Nevertheless, when primary optics is used conjugated to the LEDs, the bigger chips of HCLED require both new adapted shaped definitions to recollect correctly the output light flux, and a thermal study to test the tolerance to higher temperatures: silicon based primary optics could display limit behaviors and require other materials (i.e. glass). The new HCLED footprints are being reduced, in the new developments, approaching to the standard LEDS, what is in favor of having fewer changes in design. In Fig. 2.48 is showed a comparison of a classical high beam, a boosted version using HCLED as described in this section, and a reference high beam using laser diodes.

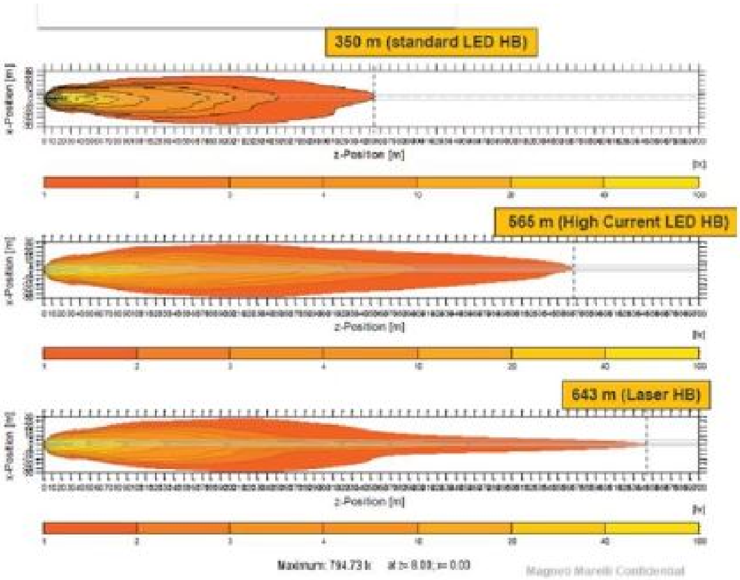


Figure 2.48: Performance comparison

The range increase with HCLED, and the higher width of the beam were highly appreciated in field tests, and confirm the interest of using this strategy for improving the beam. In low beam configurations, the usage of HCLED proved to be particularly interesting to improve the low beam in the motorway mode. The beam concentration can be increased progressively along with the usual motorway strategy (levelling up with the car speed). Besides the range, the comfort and the light flux at intermediate distance is noticeably increased (Fig. 2.49).

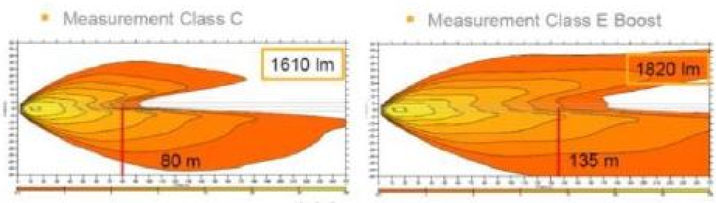


Figure 2.49: Improvement with HCLEDs

The integration of HCLED in the low beam has given a new positive subjective evaluation of the beam in motorway during our field tests. Different activation strategies were tested, i.e.:

1. Dynamic range increase with speed
2. Hysteresis
3. Dynamic range depending on steering angle
4. Drive the motorway not only with the car speed but also with other signals (camera, GPS)

Those different strategies enable us to define characteristic behavioural signatures on the lighting associated to different brands targets. In matrix and pixel beam configurations, including HCLED at the central portion of the beam, the results are similar to the ones obtained with a high beam or bi-function modules. In complicated integration configurations, an extra module, composed only by HCLED can be considered (with of course more impact to the overall design of the headlamp). With the improvement of the lighting characteristics, namely the range and beam volumes, also was improved the security and better visibility targets to the final driver. This section has presented the innovation works in advanced engineering to integrate efficiently HCLEDs into a big variety of lighting modules, ranging from standard simple lighting modules up to complex ADB ones. The main thermal, electrical and integration problems linked to the particular characteristics of HCLED could be solved or evaluated, with no particular blocking points. The benefits are not only linked to the expected higher performance in range, but also in the volume and perception of the boosted motorway function. Moreover, new operation modes could be derived (dynamic range control with speed, steering angle, and other car sensors signals). HCLEDs are to be required as an essential component future lighting module requirements and expected performances.

2.13 LED issues

1. Color LEDs are built kind of like computer chips, with precisely deposited layers of semiconductor materials. Tiny changes in the thickness of the layers can change the color of the LED's light. In addition, most white-light LEDs have another layer called a phosphor. Tiny changes in the phosphor will also lead to color changes that can make one white LED look bluish while another looks reddish and another yellowish.

2. Lumen maintenance LEDs dim and change color as they get older also. Over their lifetime heat and light exposure cause physical and chemical changes to the LEDs and the phosphors that modify the illumination. Because LEDs last 25 to 50 times as long as incandescents, those effects become apparent.

3. Cooling LEDs are far more efficient than incandescent bulbs. Incandescent bulbs turn 5% to 10% of their electricity into light, while LEDs convert about half their electricity to light. The rest of that energy – the wasted part – goes into heat. Incandescent bulbs get rid of that heat by emitting it as invisible infrared radiation – which is why hands feels warm in front of an incandescent bulb. LEDs don't emit much infrared radiation. LEDs still generate heat, so it needs to be taken away through some other method. LEDs need to be connected to heat sinks to move the heat energy away from the LED, then the heat sinks need to be engineered to get rid of that heat somehow. If LEDs are not cooled, they degrade very quickly, then fail completely.

4. Integrating multiple components. A LED light source consists of far more than the LED itself. It also contains the heat sink and the driver electronics – a circuit assembly that converts the tension from the socket into a DC voltage the LED can use. For an LED to work properly, the LED itself, the phosphor, the heat sink and the electronics all need to be failure-free. Because LEDs themselves can last many tens of thousands of hours, the other elements of the package must also be designed with that kind of lifetime – a technical challenge.

Chapter 3

LED Matrix systems on headlamps

This chapter will be dedicated to the detail analysis of LED Matrix systems, is important to take in consideration that exist a vast diversification of these systems on the market each one designed on OEM's requests, so is not possible to cover this topic at 100% but I will try to construct an overview considering some real cases applied on vehicles (serial production and prototype). Anyway I can assure that the general trends on this technology implementation will be highlighted in order to create a clear concept to the reader of actual state of art and the future implementations.

3.1 Introduction to Matrix systems [5]

Let's start showing the evolution of technological solution from the "adaptive cut-off line" to the "pixel matrix systems". The introduction of the Matrix LED headlights delivers access to various possibilities in the development of intelligent light-based assistance systems. Usually dynamic light functions were realized by mechanical rotation of the light modules. The Matrix LED headlights allow a flexible control of each LED and, therefore, the dynamic change of the light focus in front of the car. This contribution deals with the further development of lighting functions without mechanical rotation. It describes how the boundary between low and high beam disappears continuously. It further depicts how precise de glaring of road signs influences the perception of the driver. An additional lighting function supports the driver in spatial constrictions in the course of the road with a systematic light distribution. Although only a fractional amount of all accidents involving personal injury occur at dusk or night, one third of all road accidents with fatalities happen at night, which shows that the severity of an accident is significantly increased in the dark. According to statistics, during driving 90% of information is in a visual form. Poor sight and glare caused by oncoming traffic are common reasons for accidents. The downward trend of fatalities shows that the continuous development of innovative lighting functions is of great concern and underlines the importance of new and intelligent headlight concepts. Applying adaptive approaches, the vehicle lighting can be adjusted to the current traffic situation. Adaptive in this context relates to the adjustment of the light distribution and its properties on the environment (time, weather, location, illuminated objects, etc.). Through a preferably optimal illumination of the surroundings, the attempt of LBAS (light based assistance systems) is to increase comfort and above all safety, both, for the own and the surrounding vehicles without diverting them. For the development of new lighting functions it is important to have, besides new sensors for the precise detection of environment and other road users, highly adjustable actuators that offer high degrees of freedom in designing new light based driver assistance systems. In the following section the progress of system development without mechanical components is shown, in which low and high beam merge through its variety in generating light distributions, that the boundary between them slowly disappears. One of the first systems in the field of lighting based driver assistance is among the dynamic bending light. Since the light distribution of both, the low and high beam, is designed for straight stretches, the optimum illumination in curves is limited. With use of the dynamic bending light the light distribution follows the curve to direct the drivers attention to the road course. The system depends on the steering wheel angle and/or predictive route data from the navigation system and adjusts the light distribution of low and high beam to the radius of curvature. This is achieved, depending on the headlight system, by mechanical rotation of the headlight modules by up to 15 degree. Curves are better illuminated while driving, thus, increasing the safety of the vehicle. Historically, the high beam is used as the main lighting system, as the road is optimally illuminated. The low beam, however, offers the best possible road illumination without glaring oncoming or preceding traffic. Range and brightness of the low beam are therefore constrained. For convenience or fear of endangering the oncoming traffic, the high beam is, with a usage of 5 percent in Europe, rarely used. The high beam assistant therefore represents a further important step towards driver assistance to increase the high beam activation period. After enabling, the on and off operation is automatically taken by the vehicle based on sensor data. Figure 3.1-a shows the deactivated high beam with oncoming traffic. This increases the use of the high beam, optimizes the visibility in the dark and – at the same time - achieves comfort for the driver. Technically this is done by switching the high beam as soon as glaring another traffic participant is recognized or ruled out by an image processing camera system. Due to this assistant, the high beam period can be increased distinctly. As a logical step for further development of the high beam assistant, the adaptive cut-off line is considered. Through a continuous adjustment of the horizontal cut-off-line between low and high beam (see figure 3.1-b), glare of oncoming or preceding traffic is prevented and the high beam period gets increased further. This is realized by a mechanical cylinder before the light source, which nearly allows the successive switching between low and high beam. The position detection of preceding or oncoming vehicles is also based on a camera system with downstream image processing. Thus, the boundary between low and high beam blurs increasingly. The expansion of the adaptive cut off-line by the vertical component is called glare-free high beam and describes the next step in the history of LBAS. By downstream connection of a mechanical shutter, an oncoming vehicle can be masked out from the high beam cone, so that some areas of the high beam remain active and, thus, the area beside oncoming traffic is still illuminated. Figure 3.1-c illustrates the masked traffic in vertical and horizontal dimension with the upturned gap by the shutter. Depending on the traffic the shutter produces a more or less big shadow, which covers in worst case wide parts of the high beam. Due to the complexity of the mechanical approach significant restrictions on generating adaptive light distributions are given. With the use of new technologies, new opportunities and more degrees of freedom for LBAS are possible. The Matrix LED headlights divide the main beam in individually switchable segments, whereby any of these can be controlled and dimmed separately. Besides switching of different areas to avoid glare it is also feasible to highlight certain elements. The light distribution is realized by individual LED modules. By omitting mechanical components, an even more flexible adaption of the light distribution to the surrounding traffic is possible. For masking of oncoming traffic, the corresponding LEDs are determined and provided by object-sector-alignment considering a fixed safety margin. Compared to mechanical systems it is possible to mask or highlight different traffic participants or elements specifically, as shown in figure 3.1-d. Due to the increased degree of freedom in the generation of the light distributions, the boundary between low and high beam blurs further. In addition to the glare produced by oncoming traffic, glare by retro-reflective signs is considered as a further source of danger. Since the signs are designed to produce enough reflection and ,thus, illumination using the light distribution of the low beam, this leads - especially under illumination with high beam - to over-reflection of the signs glaring the driver. This increased potential risk can be prevented by the function of road sign de-glare system of the new Audi Q7 and new Audi A4. Plates and traffic signs are recognized and tracked by an image processing camera system up to 200m. The detected regions of interest are dimmed gradually depending on the signs distance and its reflecting brightness. A research study on public streets assures this feature under real conditions and shows distinctly less glare, both, physiological and psychological nature. The now homogeneously illuminated scene increases eyesight at night and - consequently - the safety of the own vehicle.

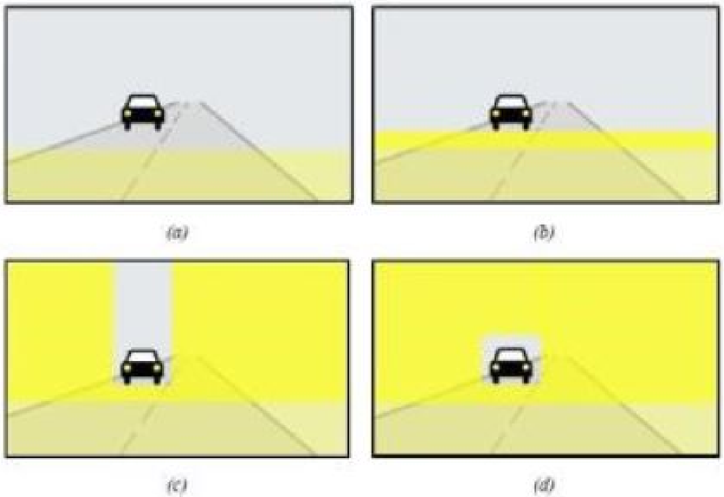


Figure 3.1: Adaptive front lighting systems

The number of headlights segments determines the resolution and the accuracy of adaptive lighting systems. A higher resolutions enables more precise illumination. With the minimization of segments, large gaps are reduced and the illuminated area increases. Through thermal and spatial constraints, the limit for current LED systems is achieved. The next step to increase the resolution providing high-resolution headlight systems is based on the concept of digital micromirror device (DMD), which provides high contrast. In this DMD system, a strong light source is illuminating an array of a high number of micro mirrors. Each mirror is controlled individually and, therefore, high resolution light distributions can be generated. Every mirror has two stable states to switch between. Through rapid tilting of the micro mirror, all dimming levels can be controlled with pixel accuracy. In DMD systems a WVGA resolutions of approximately 420.000 segments is possible. Depending on the quality of the sensor data, for example, the exact vehicle contour of an oncoming vehicle or - in extreme cases - just the head of an oncoming driver can be masked, while the rest of the scene is illuminated. In addition to these deglaring systems further marking lighting assistance systems are possible. Through high resolution DMD headlights, mould-breaking innovations for environment interaction are feasible. Communication with pedestrians through recommending light functions (see figure 3.2 left) or marking light (see figure 3.2 right) and new functions for supporting the driver in unclear situations by the active carriageway marking assist (see figure 3.3 left) are developed. When driving on narrow road sections, such as construction areas, it may be difficult for the driver to estimate the exact width of the vehicle. The optical lane assist supports the driver by projecting the exact vehicle width in form of two stripes in front of the vehicle on the road. The system is also designed for winding roads, the beams adapt the road and show the driver the ideal track. The system facilitates central driving on narrow roads and helps the driver to estimate and avoid dangerous situations in construction areas (see figure 3.3 right).

Figure 3.2: Advanced lighting functions

Figure 3.3: Advanced lighting functions

3.2 LED module on Mazda CX-5 [6]

Stanley Electric completed development of Japan's first LED adaptive driving beam (ADB) in October of 2014. The Mazda CX-5, equipped with the developed product version, was announced the following month. An ADB headlamp system controls the light distribution by switching off a portion of the high beam to prevent glare in preceding and oncoming vehicles. In this way, it can provide high-beam forward visibility regardless of the traffic environment ahead (Fig. 3.4).

Figure 3.4: Lighting functions

The main system components are its forward vehicle recognition camera, electronic control unit (ECU), and ADB headlamps (Fig. 3.5). The camera serves to detect the position of oncoming and preceding vehicles. The ECU computes the appropriate LED array activation pattern, and LEDs in the ADB array are switched on or off by signals from the ECU.

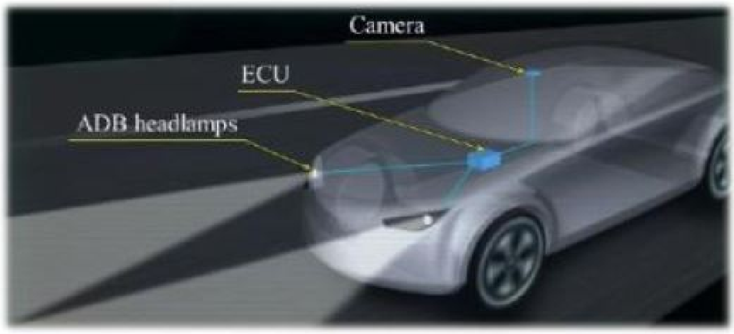


Figure 3.5: Main system components

Fig. 3.6 shows an ADB headlamp optical module, and Fig. 3.7 shows its isolux curves. The lamp unit is small and lightweight, measuring W100 x H145 x D120 mm and 40 g. The heat radiation structure is passive cooling (fanless). The power consumption is 30 W and the lighting efficiency of 40% is high. Figure 3.8 shows the individual ADB module components, comprising its lens, separator, LED array package, and heat sink. The light emitted by the LED array package is concentrated by the separator and then enlarged and projected by the lens to obtain the light distribution pattern required for the headlamp. The LED array package consists of four electrically divided segments, with individual activation control for each segment. The separator structure is the key to high lightingdevice efficiency. It is partitioned to form four apertures, with the surface processed by aluminum vapor deposition for efficient injection of the light from the LED array package into the lens. Chromatic aberration is corrected by the lens-mounted diffractive optical element.

Size [mm]	W100×H145×D120
Weight [g]	440
Power consumption [W]	27.7
Lighting efficiency [%]	30.6 (light-source luminous flux: 2450 lm) (lighting-device luminous flux: 750 lm)

Figure 3.6: ADB LED module

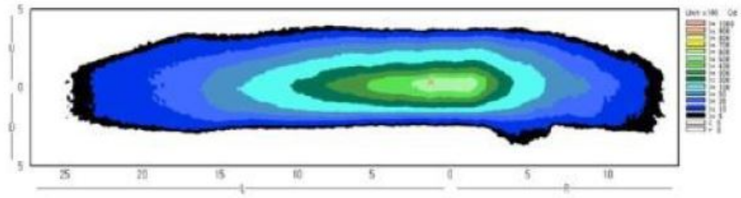


Figure 3.7: Isolux diagram for high beam function

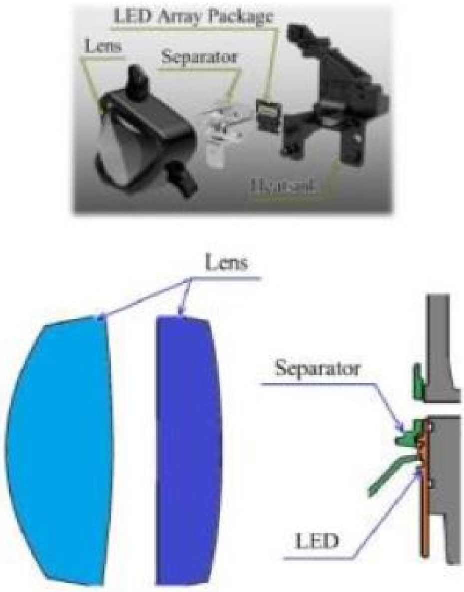
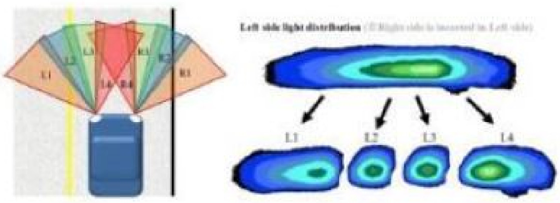


Figure 3.8: Optical components of LED module

As shown in Fig. 3.9, the light distribution pattern of the ADB module with four segments is composed of four high-beam light distribution pattern on each side of the vehicle, for a total of eight sectors.



Segment	Target angle range	Lighting target
L1	26L to 4.8L	Inside of a left curve. Outside of a right curve.
L2	8.5L to 2.5L	Left of a straight road and left (opposite) lane. Outside of a right curve.
L3	5.5L to 0.9R	Vehicle being overtaken in the same lane. Outside of a right curve.
L4	2.8L to 13.5R	Outside of a left curve.
R1	4.8R to 26R	Inside of a right curve. Outside of a left curve
R2	2.5R to 8.5R	Right side of a straight road. Outside of a left curve.
R3	0.9L to 5.5R	Oncoming vehicle in the same lane. Outside of a left curve.
R4	13.5L to 2.8R	Inside of a right curve.

Figure 3.9: Light distribution fo ADB LED module

Fig. 3.10 shows the relationship between the number of high-beam light-distribution segments in the ADB module and the cost performance. Four segments were used in the development of the ADB module described in this section in view of its high cost performance.

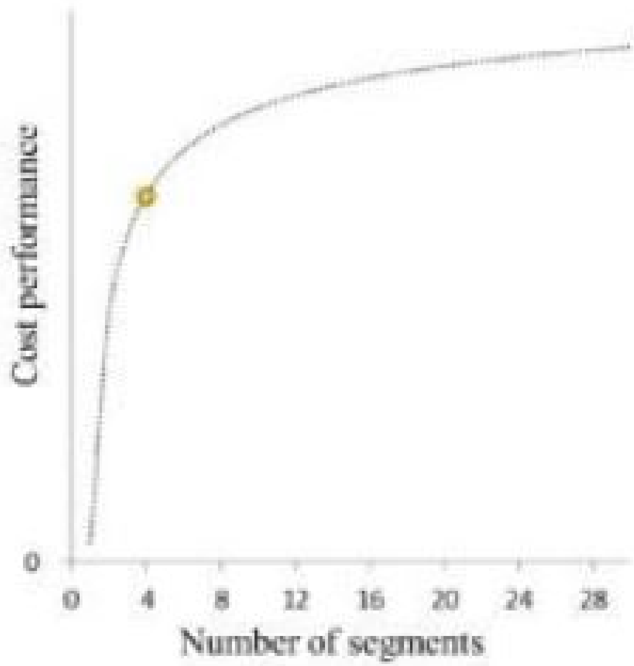


Figure 3.10: Cost performance of lighting functions

As shown in Fig. 3.11, the rise and fall in the brightness of the LED array package on activation and deactivation are controlled to avoid driver distraction. The rise time T1 and fall time T2 are determined in accordance with the state of the vehicle being driven and the forward traffic environment.

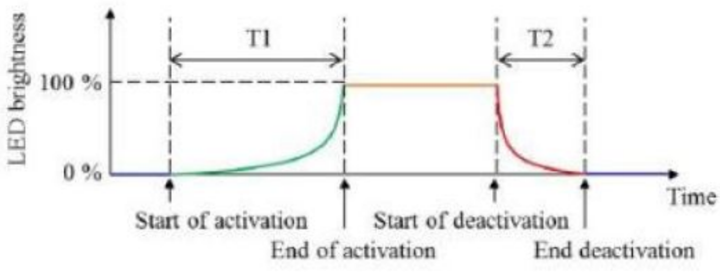


Figure 3.11: Activation and deactivation of the LED

Further research will bring new advances in the four-segment single-lens ADB module technology and development of multi-lens ADB modules (Fig.3.12) to meet the growing need for design freedom and diversification, and new multi-segmentation of ADB modules (Fig. 3.13) in the pursuit of new increases in the visibility ratio and the safety of night driving.

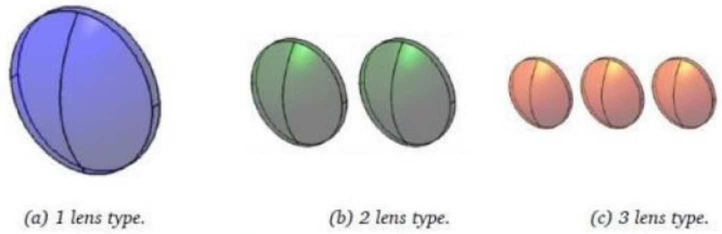


Figure 3.12: Lens types of LED modules

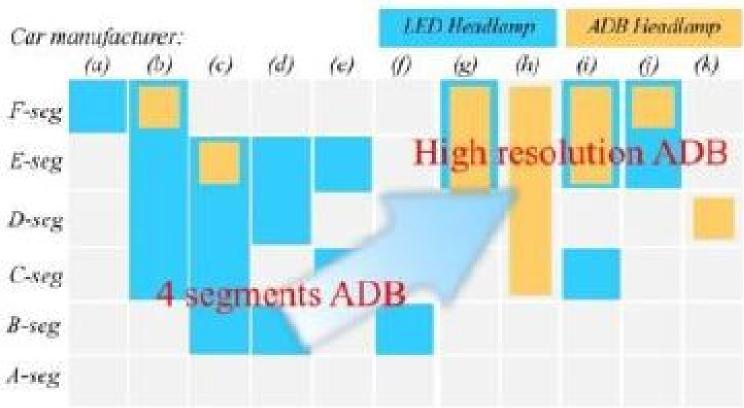


Figure 3.13: LED modules distribution

With the development of this ADB headlamp system, it has become possible for drivers to gain earlier recognition of forward road configurations and pedestrians during night driving, with greater assurance, ease, and a safer field of vision.

3.3 E-light module by Automotive Lighting [7]

Based on a high efficient LED system the functionality of a low beam with dynamic bending light plus a glarefree high beam is integrated into a projection module. The system combines the advantages of the LED light source with comfortable dimming dynamics and the high precision of a mechanical system. In this section will be presented a perfect example for the introduction of a camera controlled glarefree high beam system in combination with the adaptive low beam functions applied on cars down to the C-segment. This system can provide high performance like Xenon technology with higher comfort of the LED technology for an affordable effort and therefore shows up the potential to spread the very useful glarefree high beam system down to compact car segments. Until today, Automotive Lighting's eLight concept has already proven its performance- and cost efficiency in a number of headlamps. The 4th generation utilizes a highly efficient optical principle to combine low beam and high beam in one passively cooled module. Two-channel dimming control in combination with horizontal swivelling already enables a variety of adaptive low beam functions. By a relatively small modification, the functionality of a glarefree high beam is added to this standard module. The result is a best cost module (see Figure 3.14) providing features previously only available in the upper class segment.

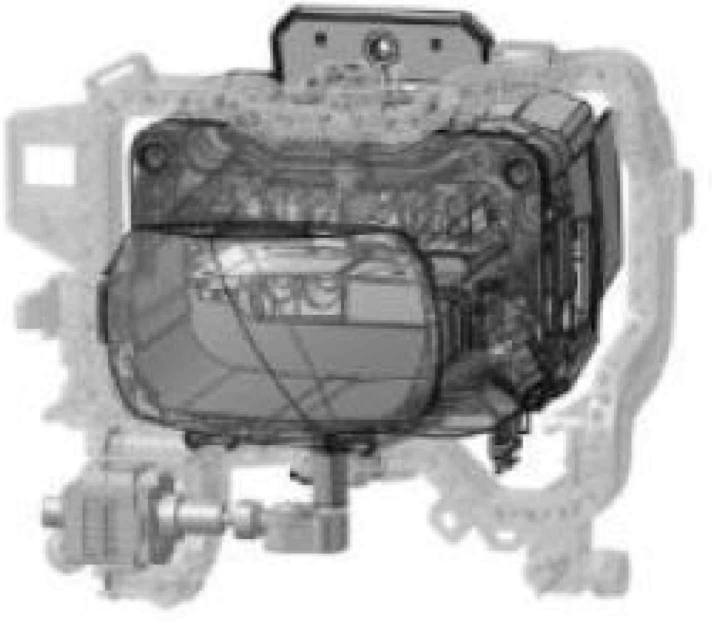


Figure 3.14: e-light LED module

The main optical elements of the eLight 4 include – besides seven LEDs for low beam and four (five HB-LEDs for non-GHB versions) LEDs as high beam light source – primary optics, a mirror shutter and a projection lens. For Low-Beam (LB) generation the primary optics collects, shapes and focuses the light of the LEDs towards the horizontal mirror shutter (see Figure 3.15).

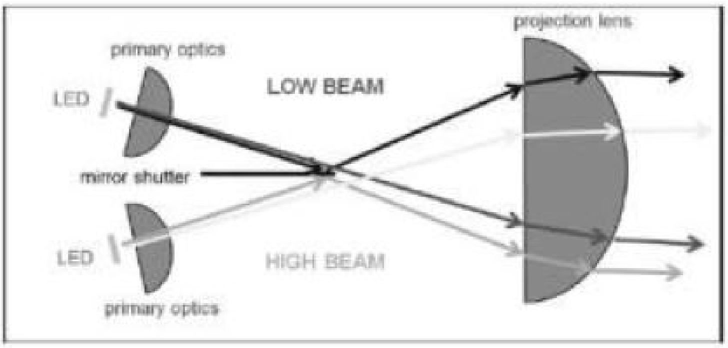


Figure 3.15: e-light LED module optics

While parts of the light can pass directly through the projection lens, some of it will be reflected by the mirror shutter. In contrast to absorbing shutters, this concept allows to utilize light, which would be lost in case of absorbing (e.g. vertical) shutter configurations. The front edge of this mirror shutter defines the contour of the light distribution on the road. The high reflectivity of the mirror shutter helps lifting the optical module efficiency to values above 50%. The total power consumption of the module is only about P =21W (including ECU), delivering a LB-flux of approximately ϕ_V = 750-800 lm onto the road, giving Xenon-like performance with significantly reduced energy consumption. Finally the projection lens projects the light distribution onto the road. It can be build either of glass or of PMMA in 1K and 3K processes to give a maximum freedom in lens styling. The eLight 4 is especially designed to deliver high performance with very slim lens designs. Mounted inside a swivelling frame with stepper motor, the light distribution of the eLight 4 module can be moved between 15°

outboard and 7.5° inboard. Depending on vehicle sensor information like turning angle of the steering wheel, speed or GPS data, a number of adaptive functions can be realized for low beam:

- motorway light: increased range at higher speed
- dynamic bending light: illumination of country road curves
- adverse-weather light: reduced self-glare in heavy rain or foggy conditions
- town light: wider light distribution for improved peripheral vision

Separate dimming channels for center and outer area of the light distribution allow for even better dynamic control of the maximum range or side illumination. To add high beam functionality, the Bi-eLight variant includes four (five HB-LEDs for non- GHB versions) additional LEDs to illuminate the mirror shutter from below (also shown in Figure 3.15). This allows illuminating the area above the LB cut-off by just using the very same efficient optical principle. No additional mechanically moving parts are necessary. To introduce glarefree high beam (GHB) functionality into the system, a two-part vertical shutter is added to the bottom of the mirror shutter to create a vertical cut off line (see Figure 3.16).

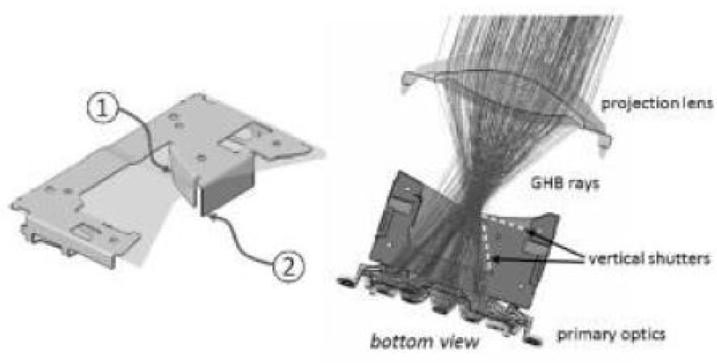


Figure 3.16: Two part vertical shutter effect

The first vertical shutter part positioned alongside the optical path reflects rays, which would be otherwise absorbed and lost. The 2nd part of the vertical shutter is located close to the front edge of the mirror shutter and blocks light on one side of the distribution, resulting in the one-sided dark area of the GHB beam pattern (see Figure 3.17).

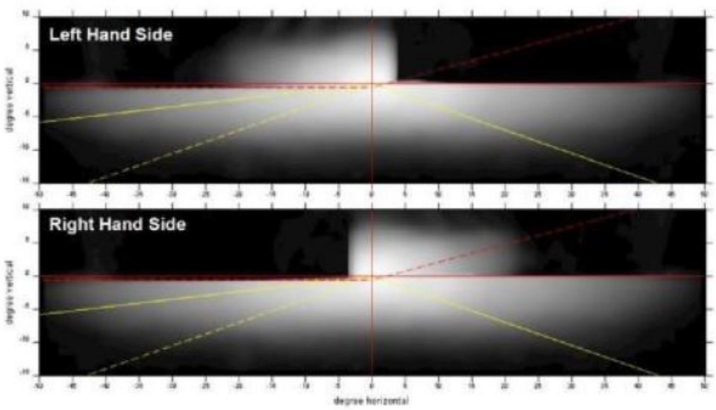


Figure 3.17: Two part vertical shutter effect, light projection

For mechanical reasons, the edge of the vertical shutter does not exactly follow the Petzval surface of the projection lens. So the image of the vertical shutter edge is not as ideally imaged onto the road, as the horizontal (low beam) edge. A too sharp vertical cut-off as well as strong colour effects, might lead to less comfortable perception of the GHB by the driver. On the other hand, a very soft cut-off may lead to unwanted stray light inside the dark area. So one of the major challenges of this configuration was to carefully balance sharpness and colour appearance of the vertical cut-off. In the complete High Beam light distribution, overlapping both mounting side patterns ensures a high illumination maximum in the center (see Figure 3.18).

In combination with a camera system to detect oncoming traffic and cars in front, the modules are swivelled independently to each side to open a gap in the HB distribution. Hence glare for other road users is effectively avoided while at the same time, the advantages of driving with HB are maintained on each side. Another advantage of the mechanical movement free Bi-function is the possibility to use dimming of the LEDs for smooth and comfortable switching of the (G)HB. Mechanical swivelling on the other hand allows continuous positioning of the vertical cut-off, which cannot be realized e.g. in low resolution fixed segmented high beam systems. The light distribution of the eLight 4 GHB is continuously adjusted according to traffic to ensure safe and comfortable driving at night.

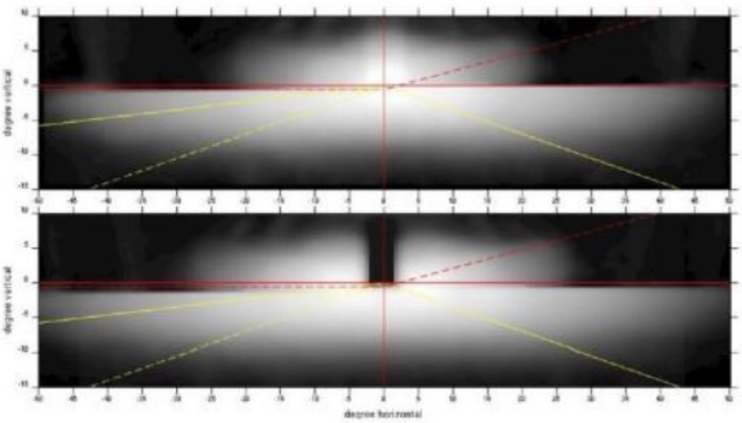


Figure 3.18: High beam light distribution

The eLight 4 GHB module adds a glarefree high beam to an already extensive list of adaptive functions in a very efficient and affordable way. Smart reutilization of the already advantageous optical concept combining primary optics and mirror shutter maintains the very good optical efficiency. Smooth and precise horizontal swivelling combined with two channel dimming control gives a comfortable dynamic light under all driving conditions. The Xenon-like performance at much lower power consumption can be delivered in very attractive slim lens designs. Overall this new member is a great enhancement in the diversity and flexibility of the eLight module family which offers variants for LB-only, Bi-function and now also GHB to choose from – integrated all in one compact module. The first Headlamp taking advantage of the eLight 4 GHB is the 2015 VW Touran (see Figure 3.19).

Figure 3.19: VW touran headlamp

Thinking a step ahead, one future variation of the eLight 4 might be a further segmentation of the high beam, using the same technical basis as for the GHB, without mechanical swivelling. Such a module would be a solution for glarefree segmented high beam in headlamps, where mechanical swivelling would not be feasible because of space or styling reasons.

3.4 Development of an integrated Low beam/ ADB unit [8]

To help popularize ADB, Koito Manufacturing Co. developed a compact, low-cost ADB system that integrates the low-beam and ADB functions in one unit. By integrating unit parts, the size of whole unit was 50% downsized from conventional module. In addition, development of new projector lens which consist of fine controlled micro structures enables compatibility between sharp low beam cut-off and softened ADB beam pattern. The first commercialized ADB adopted a system that switches light distribution automatically by moving shade. The vertical cut-off line formed by the shade will swivel in each unit, and move in line with the position of the preceding vehicle, so there will be no glare. However, there are still adjustments to be made, such as shading multiple areas individually. An LED-matrix system that solves this problem made its debut in 2014. The system, which separately controls light distribution by horizontally arranged multiple LEDs by means of on/off switching or current increase/decrease, realized many functions that did not exist before. For example, in a situation where multiple vehicles are present ahead, the system can block light to individual vehicles and illuminate the areas between them, i.e., it can minimize a light-shielding range and keep illuminating a wider area. The system can also illuminate curved roads more brightly in the direction of travel by changing the LED current. As described, ADB has enhanced safety and ease of driving through advances in technology, such as smooth switching of light distribution and wider range of illumination. Koito considers the LED-matrix to be the technology that should be widely implemented, since its high functionality and high performance. On the other hand, it is a fact that the adoption of the LED-matrix to full range of cars is not progressing, because it is necessary to provide not only an ADB unit but also a low beam unit in marketable product, which requires additional space. This paper introduces a compact LED-matrix unit integrated with low beam function which was developed to promote a broader use of the high-performance LEDmatrix that greatly improves safety. As an example of LED-matrix products, the product Koito first developed is shown on the left in Figure 3.20. It consists of two units, one for low beam and the other for the LED-matrix. The low beam unit is a reflection projector-type optical system and the lens projects light focused by the reflector. The shade placed near the focal point forms a cut-off line. The LED- matrix is a direct projection-type optical system and the lens projects the light source placed near the focal point directly.

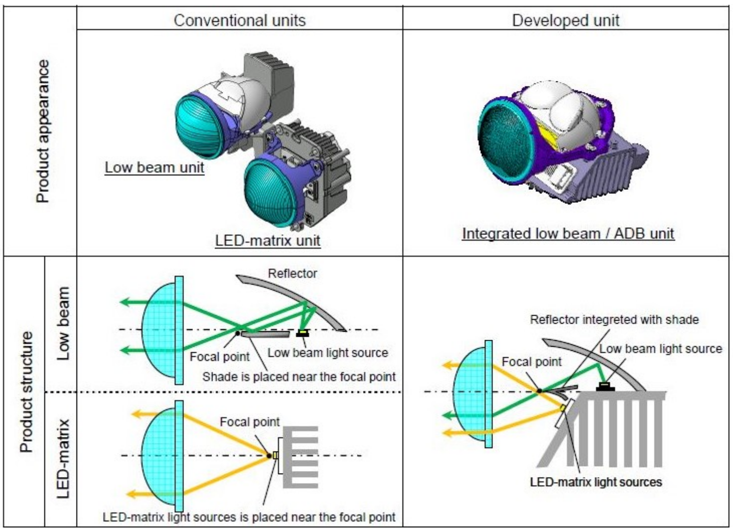


Figure 3.20: Two versions of a full LED module

In order to make the unit compact and easy to install in the lamp, conventional LED-matrix product which consists two units were integrated into one unit. By mounting both low beam and LEDmatrix light source on the same heat sink, and by sharing lens and holder between low beam and LED-matrix, the unit minimized its size.

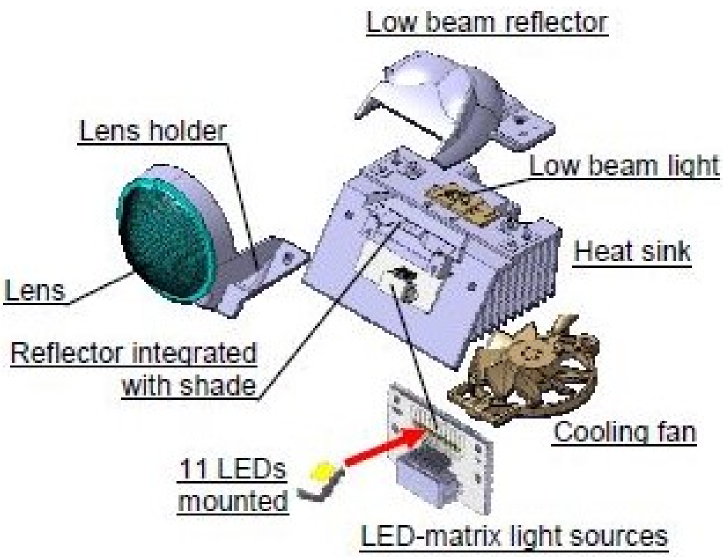


Figure 3.21: Part composition of the new developed product

The first challenge for integrating the low beam and the LED-matrix is the lens. Low beam needs an approximately 100 to 1 brightness gap between the areas above and below the cut-off line in order to prevent glare to the vehicles in front. To achieve this, a lens that has high image forming performance is required. On the other hand, the LED-matrix needs to have its individual LED lights dispersed into an even light distribution (Figure 3.22), which requires a lens with built-in diffusion control, in contrast to the low-beam lens.

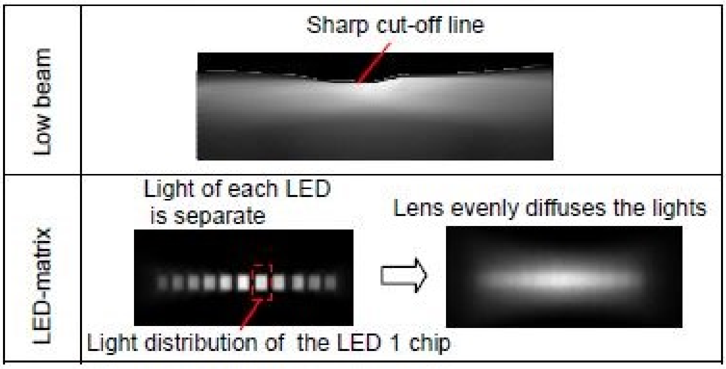


Figure 3.22: Optical requirements of matrix module

As showned on figure 3.22, the desired light distribution of the low beam and LED-matrix are very different, therefore, each requires a specially designed lens. This is one of the reasons why the conventional LED-matrix products consist of two units. Achieving two types of light control with different aims using a single lens is the first challenge. The second challenge is the placement of components. Both the low beam and LED-matrix components are placed behind the lens. Specially, the placement of components near the lens' focal point becomes complex. Because both the low beam shade and LED-matrix light source need to be placed near the focal point, it is necessary to find an optimal structure that accommodates both of them. Their conventional positions overlap, as shown in Figure 3.23, making it impossible to install both as before.

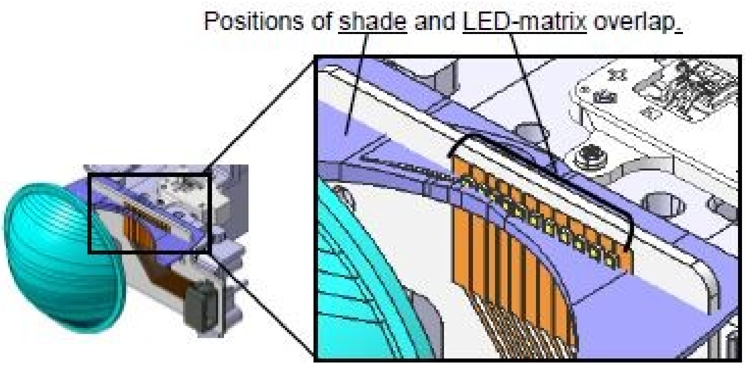


Figure 3.23: Led-matrix position in the module

The third challenge is heat dissipation. As both the low beam and LED-matrix light sources are mounted in the same unit, heat sources are concentrated and the temperature of the LEDs rises. High LED temperature reduces the LED's light conversion efficiency and lowers the brightness of LED lamps. Attempting to improve the heat dissipation performance with a larger heat sink results in a larger unit and installation becomes more difficult. Based on the above, the challenges in the development of this unit were summarized into the following three points:

- Development of a lens that achieves both the sharp cut-off line of low beam and even light distribution of LED-matrix.
- A structure that allows placement of both the low beam shade and LED-matrix light sources.
- Downsizing of the heat sink by improving heat dissipation performance.

In order to provide both low beam and the LED-matrix light distribution using a single lens, a lens that makes the cut-off line of low beams sharp and uniformly diffuses the light of an LED-matrix was required. In order to achieve these two conflicting objectives using a single lens, micro lens steps were developed. These are μ-sized fine protrusions and depressions that make up the lens surface and that control diffusion (Figure 3.24). By changing the height and shape of the irregularities, the level of diffusion can be controlled on the right, left, top, and bottom separately. Lens steps with a small amount of vertical diffusion and a large amount of horizontal diffusion were adopted in the lens we developed. For low beams, the glare that expands above the cut-off line was curbed by suppressing the vertical diffusion, and for LED-matrix, even distribution of light was realized by diffusing light horizontally.
A LED-matrix has a light distribution resulting from the projections of horizontally arranged light sources. In order for these LEDs to illuminate a long distance directly in front of the vehicle, it is preferable that they are placed near the focal point. However, when LED-matrix is integrated with low beam, this LED position overlaps with the shade, requiring the LEDs to be placed lower than their desired position near the focal point. As a result, with the conventional technology, LED light is emitted upward when low beam and LED-matrix are integrated, making it difficult to illuminate a long distance directly in front of the vehicle (upper part of Figure 3.25). Therefore, for the structure developed, a small reflector placed near the LED-matrix light sources which reflect the light to the focal point was devised (lower part of Figure 3.25). By integrating this reflector with the shade, the structure achieves both functions of a shade and a reflector in a limited space, and thereby realizes illumination over a long distance directly in front of the vehicle. Heat generated by LEDs is dissipated through the following route. The dissipation performance needs to be improved at each of the stages in this route (Figure 3.26).

1. From LED to the LED-mounting board.
2. From the LED mounting board to the heat sink.
3. From the heat sink to the air.

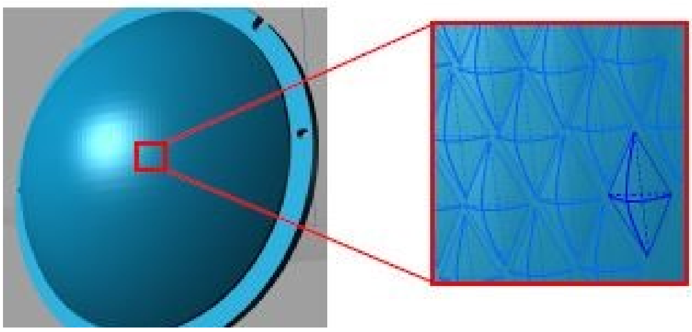


Figure 3.24: Lens steps that controls diffusion with fine protrusion and depressions

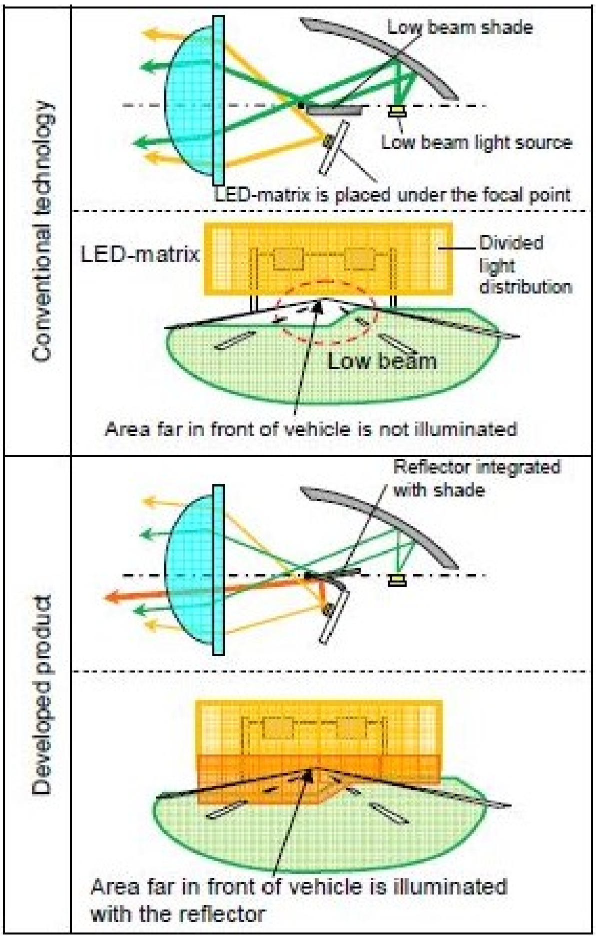


Figure 3.25: Optical characteristics of developed product

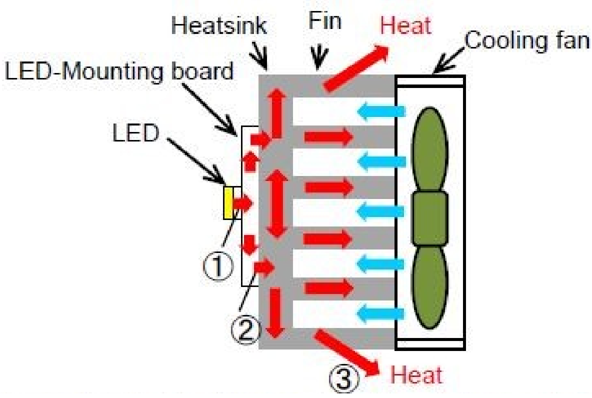


Figure 3.26: Heat dissipation

The LED-matrix light source consists of LEDs placed in a row on a board, and it is necessary to dissipate the heat from the LEDs throughout the board. Therefore, copper, which has high thermal conductivity, was used as the board material. By increasing the thickness of the base of heat sink from 3 mm to 5 mm, the structure spreads the heat underneath the LEDs quickly throughout the heat sink. By dissipating heat uniformly throughout the heat sink with this structure and with the use of aluminium die-cast alloy, the lowering of temperature was achieved.

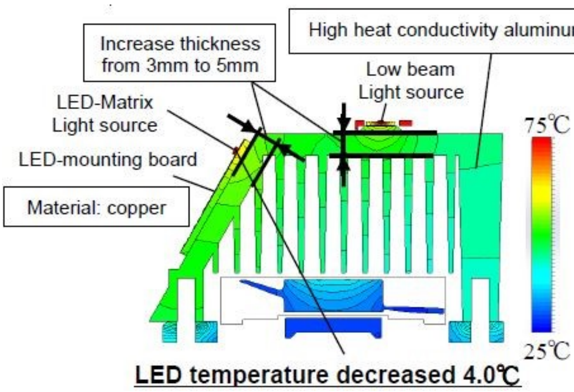


Figure 3.27: Thermography of heatsink

The heat sink with long width was designed to shorten the depth dimension. Fins are arranged to right and left direction and the fan cools the heat sink from the bottom in this structure. The fins arranged to right and left direction enable the wind to flow throughout the heat sink and thereby achieve efficient heat dissipation.

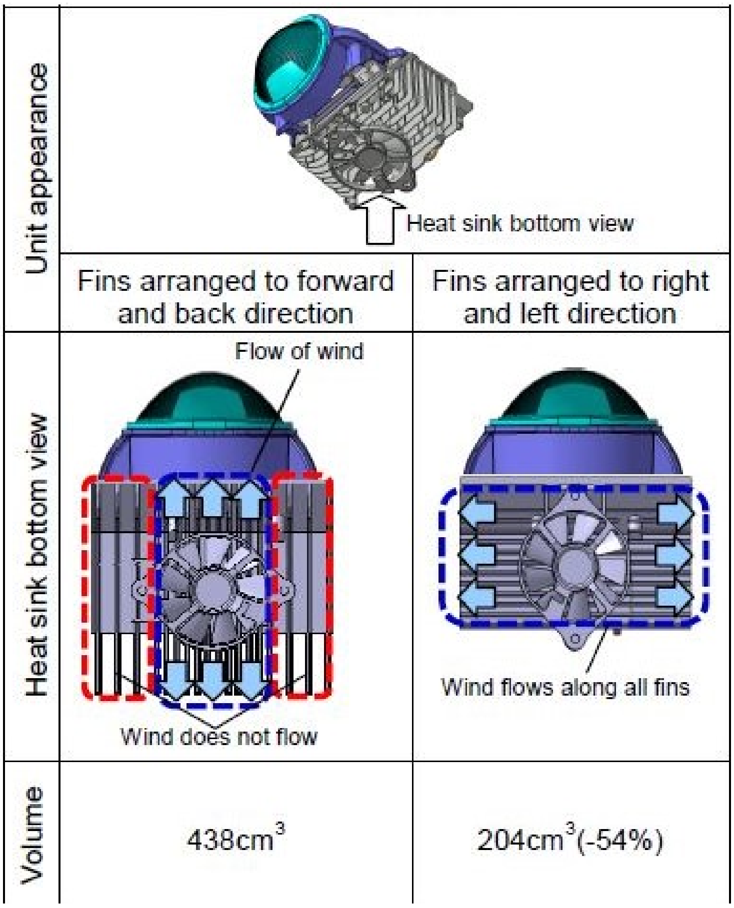


Figure 3.28: Heatsink and fan disposition

This structure achieves excellent light distribution for both low beam and LED-matrix, superior to the conventional twin unit. An actual visibility evaluation has also confirmed that the unit is sufficiently marketable.

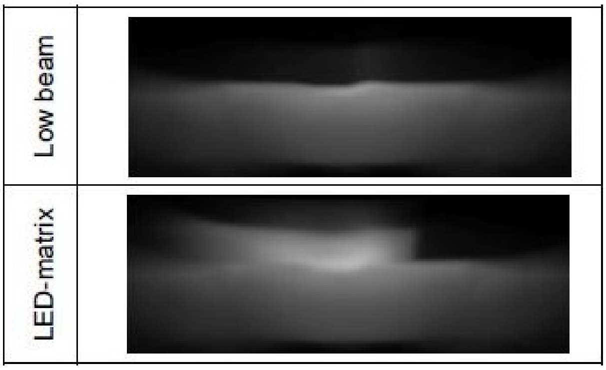


Figure 3.29: Light projection on the screen

As shown in Figure 3.31, compared with the conventional unit, 50% reduction in Volume and decrease in the number of components were achieved.

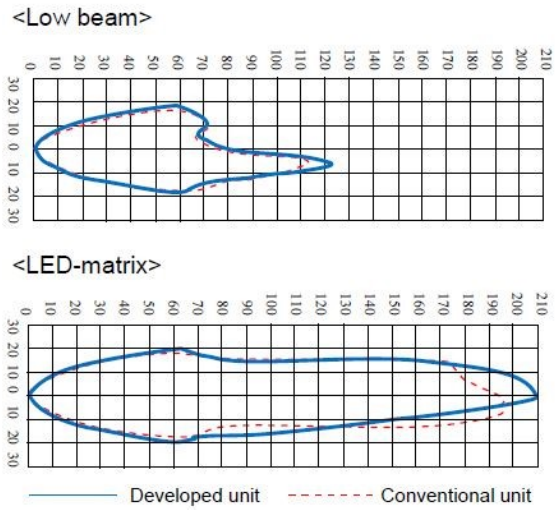


Figure 3.30: Bird view of light distribution

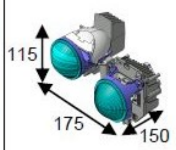
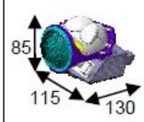
	Conventional unit			Developed unit
	Koito	competitor※ (As reference)		
		A	B	
External size				
Volume [cm^3]	2,500 (Low beam :1,300 LED-matrix :1,200)	4,400	3,600	1,270(-50%)
mass [g]	950	1,700	2,000	500 (-48%)
No. of part	37	120	200	23(-14)

Figure 3.31: Developed module improvements

3.5 Optimization of Matrix and pixel light system [9]

A description of the main parameters and criteria for the choice and configuration of an ADB lighting system, linked to performance, number of segments, cinematics and the customer perceived quality and comfort. The Adaptive Driving Beam Systems (ADB) headlamps, available today through different technological solutions as the Matrix Beam and Pixel Lighting systems, bring the automatism to front lighting and free the driver from deciding when transitions must be done, leading to a remarkable improvement in security and performance. However, the configuration of the system can be driven by the OEM strategy, by the choice of the number and distribution of segments / pixels, dimming and cinematic strategies inside the beam, vertical adjustment, camera main characteristics, etc. The headlamp, that is fundamental to the car style signature in lit-off state, creates light and technological signatures for the front lighting. Some of the PSA Group strategy will be presented for the development and integration of ADB systems to enhance and create identities linked to different brands, with the best technological trade-off. Even though the automation of the low / high beam transitions and the almost ideal light distribution on the road, provided by the ADB systems, are the most striking characteristics of this kind of lighting system, from the technological point of view, the first most important criteria for evaluating the performance of the headlamps are still the measureable total flux on the road. Those values of total flux for the low and high beams quoted independently are still the metrics for the comparison for a new headlamp development against other reference car lightings. However, in the other hand, the static measurement represented by the total flux must be conveniently weighted by the total usage of the low and high beam. If two lighting systems are compared, one with and another without an ADB high beam, an eventual reduction of flux for the low beam is typically largely compensated by the added flux coming from ADB high beam for much longer periods of time, thanks to its automatic activation. Moreover, the different light distribution shape and range of the ADB high beam adds up to the visibility range and predictability.

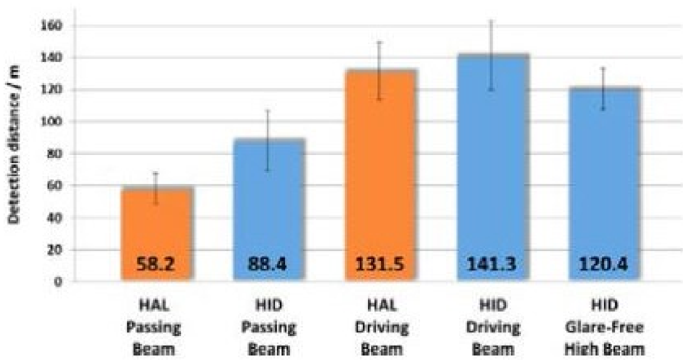


Figure 3.32: Improvement of the detection distance with ADB systems

However, for dimensioning the flux performance of the lighting modules, those high fluxes are still mandatory, and it is not necessarily the good equilibrium of nominal flux /module vs. combined flux usage. The latest is highly dependent on the technological choice. Those over-fluxed solutions have an important impact in the number of LEDs, the module dimensions, the style possibilities, and of course, power consumption. If a new mindset has still not evolved with the present “matrix beam” systems, perhaps the pixel light solutions could be rationalized in terms of total flux, where the beam should no longer divided into low and high as is used to do now. Nowadays is possible to highlight that in the offer of ADB system from the main suppliers a big number of choices and ‘customizable’ ADB modules, choices ranging from 3 to 5 segments up to 20 or more – for the matrix beam concepts or, in the world of the Pixel lighting, an announced competition towards the maximum number of pixels (> 64 pixels). After having talked about the overall performance and flux, the second question is: what is the best choice for the number of segments? Many engineers associate the number of segments with a better performance, a ‘must have’ to place the company at the same level of the competitors.

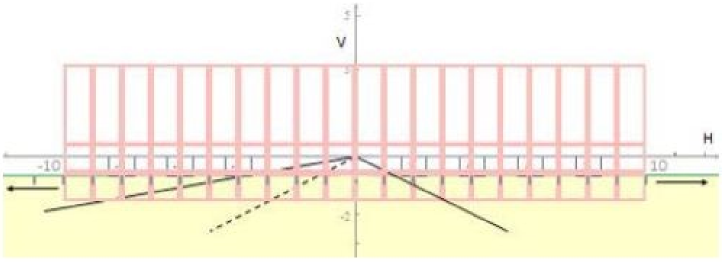


Figure 3.33: ADB number of segments

The first ADB systems in the market, had the ‘mechanical’ solutions for creating a ‘mono-tunnel’ ADB, using either vertical or horizontal rotating shields inside projection system modules. This kind of device, with different levels of accuracy, and the combined movement of modules, provided quite smooth transitions and an almost continuous tracking of the incoming or followed cars. That behaviour, in terms of performance was quite optimized.

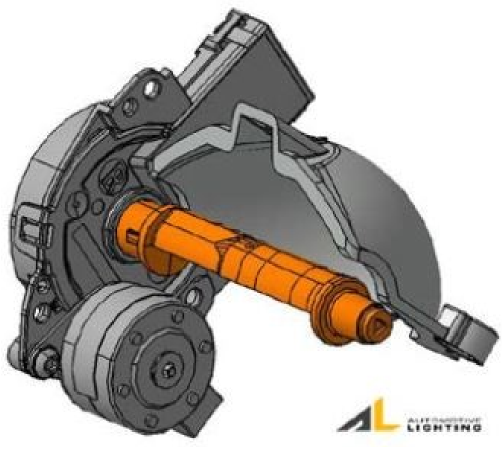


Figure 3.34: ADB module with a mechanical rotating shield

The next step, with the multi-LED ADB modules brings the main advantages of having a reduced number of actuators, almost no mechanical movement or moving shields, volume reduction. But, in the other hand, now the beam are sliced into a finite number of segments, and the transitions can be visible and stepped, depending of the road shape, speed and traffic density. New strategies were developed to overlap segments and to improve resolution and contrast of the segments to reduce the perception of the transitions and for a better homogeneity. At the OEM level, hundreds of hours in night drive tests were performed, trying to decide what is the better compromise: starting with 5 to 6 segments or going directly to 20 segments or even more? It’s better to focus on the final customer: if it’s not possible to have perfect smooth transitions the goal should be to have fewer perturbations during the longest periods of time during his travel. The best solutions today rely on segments with different widths, thinner and overlapping at the car axis, and with peripheral segments progressively wider, in order to achieve a better precision in adjusting the different central dark tunnels in width, when running on the most frequent straight line roads, or for big road radius. Of course, for mountain and sinuous roads, the transition will be quite flashing and with visible transition steps. However, from the many choices in the market, the total flux of the headlamp also increases with the number of segments, and the performance evaluation related to the number of segments cannot be done at constant flux. At the end, looking for absolute performance, the tendency is to select the highest number of segments. However, if more powerful LEDs could be used in a configuration with fewer segments, certainly new reasonable combinations could be found. The usage of a fewer number of LEDs can bring up the beneficial advantages already mentioned before: cost reduction, lower power consumption and reduction of the module size. The same analysis can be done with the pixel light models, made up of an even bigger number of dices arranged in matrix disposition. The best compromise will be achieved by previously determining the most dynamic zones in the light distribution useful for the driver. Those zones must be covered by a bigger number of smaller pixels using some overlapping techniques. Elsewhere, the road can be mapped into bigger pixels, with a coarser distribution. It will be also important to play with automatic dimming and finer position adjustment. In conclusion, today there are no solutions on the market flexible enough to increase the total flux keeping a lower number of segments. Solutions are pushed towards the maximum number of segments which are not necessarily the best optimized solutions. As were mentioned before, the customer comfort related to night driving comes from the combination of many factors. From the experience point of view, the first positive reaction from customers facing an ADB system is the automatism, the driver has no longer to worry about the tedious and repetitive decisions of switching between low and high beam. Here the reliability of the camera, the detection system and algorithms, are key factors. The experience of having malfunctioning, badly adjusted systems, intermittent behaviour, is a source of customer's complaints. Also linked to the camera and to the lighting strategy is the precision for defining the dark zone width, its vertical positioning and multitunnels management. Despite the importance and the interplay of the lighting modules and the camera system, there are only few suppliers in the market that can provide to the OEMs a complete and optimized solution. When the camera and the lighting modules are sourced separately, it takes much longer development times to tune the whole system. The customer comfort is also important when he is not the driver, and is submitted to the ADB system. Many optimizations are possible, related to the definition of the light tunnel close to preceding car. By diming or levelling properly the corresponding side segments that define the tunnel, it's possible to reduce glare at the preceding car central and side mirrors, and to the light projected on the around the preceding car. This kind of optimization can be improved in a pixel light systems, where pixels linked to that kind of glare can be simply dimmed or turned off. In conclusion, the main customer comfort factors in connection to ADB lighting are the automatism, light flux, smooth transitions at least at the central zone. The possibilities of style and integration of new technologies as the ADB systems depend on the size and number of modules, total power, the volume and position of heat sinks (active or passive). All of those factors are associated to the choices mentioned before: overall performance, number of segments.

Figure 3.35: Peugeot signature

Moreover, as the headlamp is a key component for the car external style, the OEM choices on how to put in evidence the technological jewel it represents are decisive for the choice of the technology: reflector or projector systems, number and disposition of the modules.

Figure 3.36: Citroën signature

Generally speaking, the stylistic choices today point towards high compact and thin modules, with high levels of standardization and associability, in order to reduce development and production costs. This quest for compactness bring new challenges linked to thermal management, high refractive materials for lenses, and the improvement of efficiency of the LEDs themselves.

Figure 3.37: DS signature

Besides, even if the main concern today for the integration of ADB modules are reserved for the high end level cars, we must be prepared for the progressive implementation downstream that will follow, in a decade or two, to medium and entry level cars. Certainly will not be maintained the same levels of performance and technical solutions, but the market will become more and more demanding on comfort linked to the automation ADB solutions afford. The concept, integration and optimization of ADB systems is a complex task linked initially to the correct definition of the required performance levels that can no longer consider as a simple addition of low and high beams, but rather a holistic light distribution turned on almost all the night driving time. For the definition of the number of segments and pixels, the optimization should take as well into account the frequency and purpose of the different segments, whose width should be adapted according to its angular position. Last but not least, the ADB solutions cannot today replace completely all the satellite functionalities, as the bending lights, marking light, cornering lights, also important for security and comfort driving. The pixel light solutions are being improved to fulfil those functions also, but there will be certainly physical and/or stylist limitations that has to be improved.

3.6 Feedback from 6 Matrix systems on the market [10]

The first Matrix Technology carrier arrived in the market in 2013. Following the international classification for platforms and motor vehicle segments, this car was placed in the E segment. The sequential rollout of the Matrix LED technology reached quickly the lower segments, so that meanwhile platforms in the D-segment and C-segment, (executive, large and medium cars) are available with the option of that interesting new technology. (see Fig.3.38, 3.39, 3.40). Three more platforms are available in Europe and Asia with a segmented high beam, carrying different nomenclature nameplates for such technology approach.

Figure 3.38: Audi A8 SOP 2013, Audi TT SOP 2014

Figure 3.39: Audi A7 SOP 2014, Audi A6 SOP 2014

Figure 3.40: Audi Q7 SOP 2015

Matrix technology is composed of three major elements: first a camera system to detect oncoming or preceding cars, second a software to classify the objects and define the headlamp reaction and third a headlamp system to execute the ADB functionality. Some more factors like direction prediction, traffic density and environmental conditions are as well important elements that have to be considered while defining the matrix activation. In Fig. 3.41 an example of night drive evaluation is given.

Figure 3.41: Example of a Matrix activation scene

Several benefits add up to the matrix technology, most important are e.g.:

- The driver is able to concentrate much more on his driving task, because the activation and deactivation of the high beam function is done by the Driver Assistance System in the car.
- The switching on and off of segments inside the high beam light distribution of a matrix system does not interfere with any distracting movement of the low beam distribution on the street, generated by swiveling motors.
- Due to the fact that significant luminous flux and illuminance is provided above the cutoff area, surrounding topology changes like ditches or small hills aside the road with different inclination to the street are largely visible. Regardless from correct percentage values, the large visibility area increases the drivers view and adds safety.
- Potential objects left and/or right to the oncoming car become visible, because the high beam illumination provides higher distance visibility versus the conventional low beam.

- Since the matrix beam activation is automatic, the activation time on country roads achieves more than 85% versus 3% with conventional individual high beam switching.

With the selected benefits above, traffic safety is highly and positively affected.

Matrix LED headlamp performances

For Matrix high beam 12 to 25 LED were used per headlamp to generate segments in reflection or projector type modules. Two scenarios have been investigated: one Scenario with an oncoming car, another scenario with a preceding car. In order to make the different headlights comparable, similar dark zones have been virtually generated.

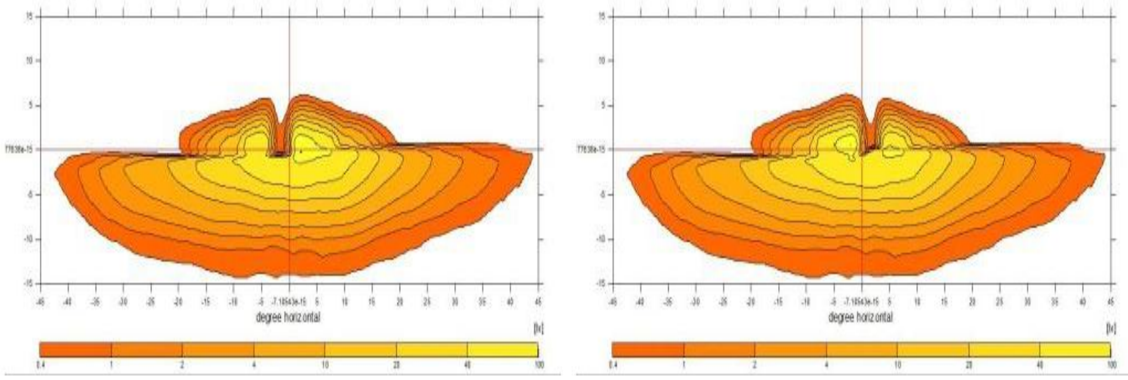


Figure 3.42: Isolux diagrams for: oncoming car situation (left), preceding car situation (right)

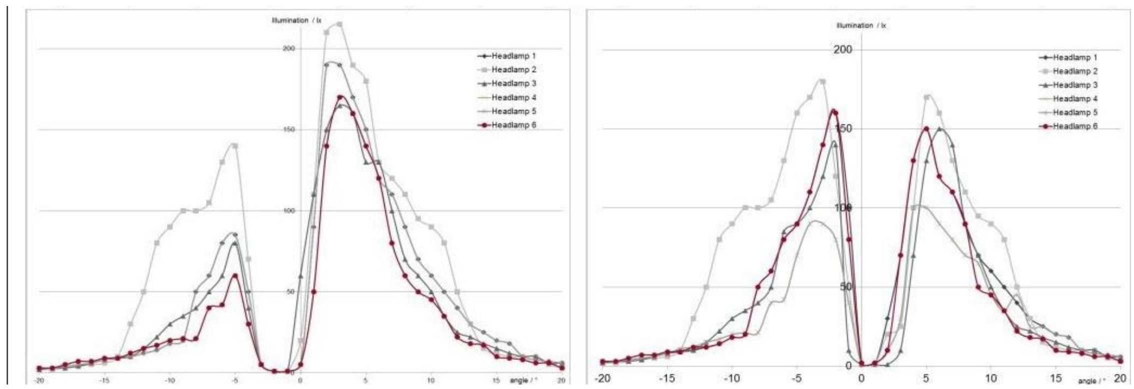


Figure 3.43: Bird view diagrams for: oncoming car situation (left), preceding car situation (right)

The analysis of the light distribution shows that a good gradient from 2 to 4° can be achieved by each of the technologies. The width of the light distribution remains like in a standard high beam, and only the blocked segments make the difference. Depending on the driving current situation for each LED, illumination levels of more than 200 lx can be achieved.

Traffic safety investigation

Without oncoming or preceding traffic, the matrix system behaves like a normal high beam. Like shown in Fig. 3.44, any oncoming car produces glare, reducing the local contrast sensitivity and object detection ability. One of the most critical situations is that objects are quasi concealed while the reduced visual performance of the driver occurs.

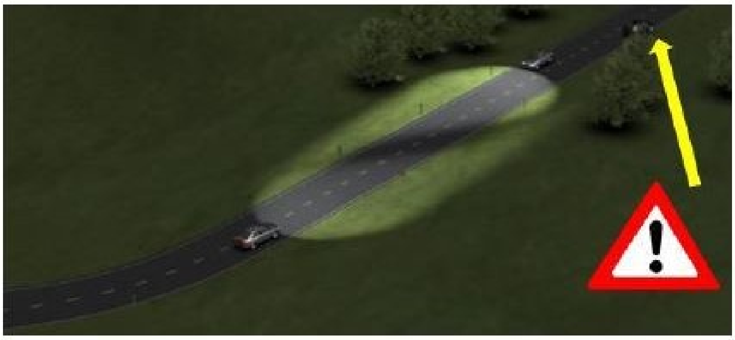


Figure 3.44: Low beam illumitation during night

This scenario was rebuilt in a test setup in order to investigate the real differences of detection distances under oncoming glare conditions.

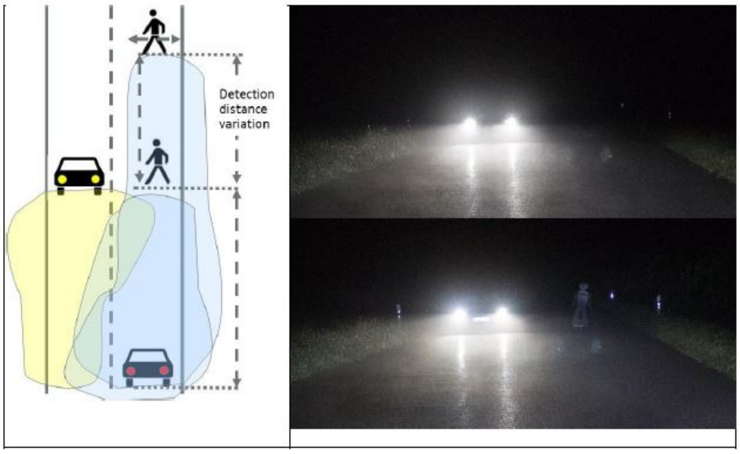


Figure 3.45: Performance increase with matrix system

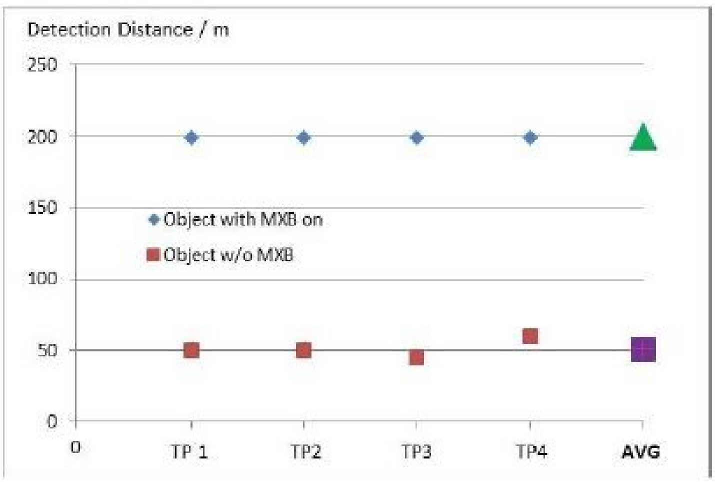


Figure 3.46: Low beam vs matrix detection distance

This investigation was planned to highlight the real street scenery benefits of matrix systems. A car with activated headlights was opposing a Matrix headlight system. The street was without retroreflective lane markings and had wet surface and regular delineators. Distance was set to 50 m. A moveable pedestrian dummy was placed in lane of onwards driving direction. The dummy was kept in the lighted area of the Matrix system, about 3° away from the nearest headlamp. The dummy was painted in a silk-mat (RAL7016 dark anthracite grey). Both low beam and Matrix beam detection distance was recorded. (Setup and pictures in Fig.3.45 and.Fig.3.46). Threshold was the detection from driver's position. As expected, changes in each position of the triangle between position of the glare source, position of the dummy and the driver's eye generate varying results. Since the angular distance between glare source and dummy object affects significantly the threshold detection, the experiment can only be considered as a snapshot. Independent, the results are dramatically positive. The increase of a factor of 4 is due to the higher amount of illumination to the object under the given glare condition. The dramatic experience for the test persons was, that the dummy immediately disappeared when the low beam was used as single light source. The original start distance was set to 100m, but only around 55m at the opposing car level first positive threshold could be found. Generally it can be assumed, that any unlit and non-retroreflective grey or dark object that in a situation like described above appears would not be visible in any distance behind the oncoming car. With the investigations provided in literature it can be stated that nighttime driving on rural roads is dominated by adaptive driving beam situations. Depending on the investigation, the usage time exceeds 85%. That means, that situations like described above will be avoided in many cases. Higher detection distances as found in the investigation may also have impact on the general ability to better evaluate the nighttime street scenery, better analyse and assess objects in the traffic areas and to concentrate earlier and better on potentially dangerous situations. So additionally to the benefits described above a traffic safety increase of a visibility factor of 400% can be stated.

Customer reactions

The amount of reactions to the headlights increased significantly and very positive. Especially the improved illumination level was part of many comments. Since the limitation of headlamp range by the traditional cutoff is eliminated, nighttime driving was rated more comfortable than before. In all benchmark tests the matrix headlights have received highest ranking with maximum score. The first Matrix light test in a journal for 15 series cars ended in the (translated) summary: "..the Audi A8 with Matrix-LED has with big gap the best light". A recent lighting test report comparing 12 different headlamps from June 2015 comments (translated): "…persons at 12m distance along the roadside are with low beam only partly visible,.()..in contrast with the popped up (Matrix) high beam they are good visible…()… the best light in test." General Automobile test reports usually do not concentrate only on lights. But a comment like :"… It's all desirable stuff, though – my personal highlights are the LED Matrix headlights…" is showing the positive and concious mentioning of Matrix systems as a remarkable feature. Matrix LED headlamps provide improved visibility, customer satisfaction and improved safety. The investigations showed a factor of 4 for the detection distance under opposing and glaring traffic conditions. All systems provide a broad and bright high beam without glare for oncoming or preceding cars. Customer feedback and journalist feedback is throughout positive, Matrix systems are dominating the lighting test reports. Matrix LED headlamps have a clear and appraisable benefit for the driver. Every accident that can be avoided does not appear in any statistic. That is a good news for a “silent” safety technology, nobody can remember avoided accidents. With such summary an outlook is rather simple: Matrix LED headlamps will penetrate the market rather quickly and in short time become a mandatory option in the lighting world with fast top-down implementation speed.

3.7 Field test on optimal traffic sign illumination [11]

Due to their retroreflective properties, the light is reflected back to the driver and may result in glare and thus in low identification distances. This kind of glare is designated as self-glare, since the driver is dazzled by light from his own headlamps. First static studies have shown, that traffic sign glare illuminance is angular size dependent. While approaching a traffic sign, it appears to get larger, whereby illuminance has to decrease in order to avoid glare, especially when driving with glare-free high beam. For this reason, first OEM’s already cut out traffic signs from the light distribution to avoid this effect. However, the luminance has to be adapted, since the transition between light environment and dark signs leads to poor legibility. At the Technische Universität Darmstadt a study is performed to find the optimal traffic sign illumination that does not result in glare (through an outshining of the traffic sign) and maximizes the identification distance. This is done by a dynamic field study, in which a vehicle with glare-free high beam passes with constant speed, traffic signs located to the left and right side but also in front of the driver, simulating a sign in a bend. After passing with low beam (lower limit) and high beam (upper limit), high beam is dimmed stepwise to simulate different levels of masking out traffic signs. To find the optimal masking level, identification tests are performed for each high beam intensity. By combining the identification distances with the identification luminance, the glare rating and brightness rating, the optimal traffic sign illumination can be found. Furthermore, illuminance is measured during each passing process, both at the traffic sign and at driver’s eye position. To receive a correlation between measured illuminance and distance, a GPS system is placed on both vehicle and traffic sign. To investigate the optimal illumination of retroreflective traffic signs, a field test is performed in which three different traffic signs are examined. In order to investigate the worst-case scenario, the traffic signs have a characteristic that result in a maximum retroreflection. Therefore, all signs belong to class RA3, which is mainly found on highways and some country roads. The most common traffic signs on these roads are guide, placename and speed signs, which in Germany are painted blue-white, yellow-black and whitered accordingly. Three different traffic sign locations are used – to the left, to the right and in front of the vehicle, whereby the last scenario represents a traffic sign in a bend (see Figure 3.47). Their geometrical arrangement is taken from the German road traffic regulation (StVO). To find the optimal illumination, a vehicle with glare-free high beam is used, in which the high beam can be dimmed. By doing so, different illumination levels can be examined. Within the framework of this examination, six high beam intensity levels are chosen – 0 %, 26 %, 36 %, 51 %, 76 % and 100%. Zero percent stands for switched off high beam and represents low beam whereby 100 % equals fully activated low and high beam. The vehicle is equipped with a photometer to measure the illuminance that is reflected back to the driver. A GPS receiver allows the correlation of the illuminance with the distance to the sign.

Consequently, each traffic sign is also equipped with a GPS system and a photometer, to measure the illuminance while the vehicle approaches. The test subject accelerates the vehicle and passes the signs with a constant speed of 60 km/h. The subject is asked to push a detection button, as soon as he is able to read the information on the traffic sign. To ensure, that the subjects do not accustom to the traffic signs, the blue guide sign as well as the yellow place-name sign are changed in a random order from "Darmstadt" to "Dortmund", two German towns whose spelling appear to be similar when read from distance. The speed sign is also changed from "50" to "60" for similar reasons. After passing the traffic sign (TS), discomfort glare and brightness of the sign is rated by the subject. In the following figure, the test arrangement can be seen. Each run around the circuit is repeated three times in order to statistically analyze the data. In sum, 21 subjects participated in the test with an average age of 30. The youngest is 22 and the oldest 53 years old.

Figure 3.47: Field test layout on the August-Euler-Airport in Grisheim

For every run, the GPS data is saved for every traffic sign position as well as for the test vehicle. The software in the test vehicle also synchronizes the detection-button with GPS time, so it is possible to determine the exact distance between the test vehicle and each traffic sign at the moment of identification (button pressed). Additionally to the GPS and the photometer data, luminance pictures are taken every 25 m from 75 m up to 200 m distance for all six intensity levels (5 HB levels + 1 LB) thus allowing to determine the optimal luminance which is need to identify each traffic sign. Because visual perception differs from person to person, the absolute identification distance is normalized to the respective low beam value. In Figure 3.48 the identification gain and the standard deviation can be seen for the examined HB levels for each traffic sign (TS). The mean absolute low beam identification distance for the speed signs (TS 1 and TS 3) is approximately 125 m and for the place-name signs (TS 2 and TS 4) 75 m. This differences result from the different sign and text sizes. After analyzing the identification gain of all subjects shown in Figure 3.48, a clear increase in the mean high beam identification distances can be seen when comparing them with the equivalent low beam distances. However, a high standard deviation of the data occurs, which is probably caused by the different visual perception of each examined subject. A statistical analysis shows for all traffic signs that, there is no significant difference between the examined high beam levels. For this reason, the perception data in terms of glare and brightness of the traffic sign in accordance to the high beam level is taken into account.

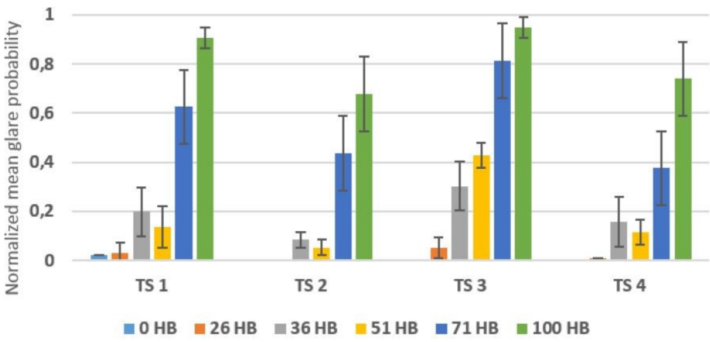


Figure 3.48: Identification gain of the different HB levels for each taffic sigh (in relation to LB)

Figure 3.49 shows the normalized mean glare probability of all subjects in accordance to the different high beam levels for each traffic sign. A possibility of “1” means that the 21 subjects always feel glared.

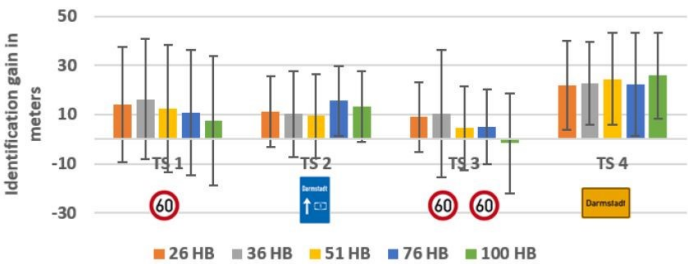


Figure 3.49: Normalized mean glare probability to different high beam levels for each traffic sign

In contrast to the identification gain shown in Figure 3.49 a clear correlation between glare rating and high beam level can be seen – with increasing high beam level, glare possibility also rises. This results for example in a 90% glare probability when approaching traffic sign 3 (TS 3) with fully activated high beam (100 HB). Here, the glare probability reaches its maximum for all traffic signs. It continuously drops again with decreasing high beam level and reaches its minimum, as expected for low beam (0 HB). As this field test is also designed to compare the different colors and positions, the examined traffic signs are divided into two parts. In the first part, the speed signs TS 1 and TS 3 (located in front and on both left and right side), the glare probability increases and is at least 50% higher with two traffic signs compared to one that is located in front of the vehicle. Furthermore, the glare probability does not exceed a mean value of 20% when using a high beam of up to 51%. When comparing the place-name signs (TS 2 and TS 4) that are located both on the right side, only differing in their color (blue, yellow), no significant differences occurs. Thus leading to the conclusion that a blue and a yellow sign with the same dimensions and the same retroreflective properties lead to similar glare probabilities. In addition to the glare rating, the subjects are asked to rate the brightness of each traffic sign in a scale from “1” to “5”, whereby “1” represents a value for too dark, “5” a value for to bright and “3” an optimal brightness respectively. Figure 3.50 shows the mean brightness rating for all subjects in accordance to the different high beam levels for each traffic sign. It is striking, that as with the glare rating, a correlation between brightness and high beam level appears. This means that with increasing high beam level, a traffic sign outshines and starts getting to bright. Remarkable in Figure 3.50 is the fact that low beam (0 HB) is rated from all subjects as to dark and on the other hand, fully activated high beam (100 HB) as to bright. In the following, the brightness rating is divided into 3 parts – a too dark part below 2.5, an optimal part between 2.5 to 3.5 and a too bright part above 3.5. For TS 2 (blue place-name sign) and 4 (yellow place-name sign) the optimal brightness results for a high beam level between 26 and 36%. The same value is also true for the speed sign located in front of the vehicle (TS 1). While combining these results with the glare probability shown in Figure 3.49, a maximal mean glare probability of 20% occurs for a high beam level of 36%, whereby for a high beam level of 26%, the glare probability significantly drops below 5%. Thus, the optimal traffic sign illumination to avoid glare and to have an optimal brightness has a high beam value of 26%.

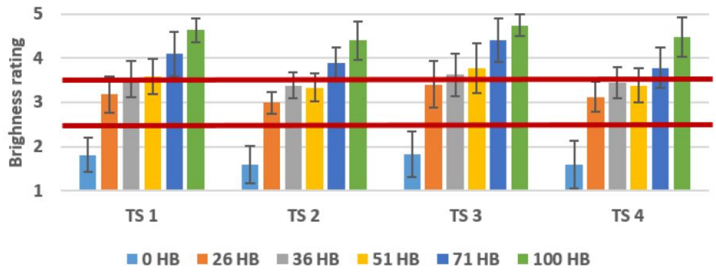


Figure 3.50: Mean brightess rating in relation to high beam levels for each traffic sigh

In order to calculate the luminous intensity of the headlamps for the optimal brightness, as described above, the illuminance measurements are taken into account. With a high beam level of 26%, the measured illuminance at for example 50 m, is at TS 2, TS 3 and TS 4 approximately 6 lx. These traffic signs are positioned beside the lane, while for the first traffic sign, which appears in front of the vehicle, the illuminance is approximately 10 lx. These illuminances can be converted with the photometric distance into luminous intensities and correspond to 15000 cd and 25000 cd respectively. A statistical analysis shows that there are no significant differences among the examined high beam levels varying logarithmically in a range of 0 to 100%. However, when considering the subjective perception, differences occur both in glare and brightness rating. For high beam levels up to 26%, which correspond to luminous intensity of between 15000 cd and 25000 cd depending on the position of the traffic sign, less than 5% of the examined subjects fell dazzled and rate the sign as optimal illuminated.

3.8 Adverse weather light [12]

During night time driving, modern adaptive headlamps illuminate the street excellently. The driver has optimal visibility, the regions of oncoming traffic are shaded and nobody is glared. This is not the case for adverse weather conditions. Caused by high luminous intensity during rain, snow or fog, the self-glare for the driver (Figure 3.51, left) might increase compared to driving with conventional Halogen systems. Also, drivers of oncoming cars can be glared by high luminous intensity in their directions (Figure 3.51, right). So, there is a need for special illuminating strategies for adverse weather conditions.
Previous research investigated the question how to realize light distributions for adverse weather light. Most of those relevant studies are quite old. At that time, it seemed difficult to integrate the necessary actuating elements in a headlamp. Adaptive systems which detect other cars and optimize thereby the light distribution couldn't be

realized 20 years ago. Nowadays adaptive headlamps are state of the art and different technologies are under construction to realize very high resolutions of the light distributions. Due to the technical developments the feasibility of adverse weather light seems to be possible. On the one hand the concepts of the older studies can be realized and evaluated in empirical tests. On the other hand, new adaptive strategies can be implemented. In the 1990s, when the discussion on adaptive light distributions started, the integration of adverse weather light functions was considered right from the start. Until then, the fog light was the only light function being adapted to adverse weather conditions. Now, the function of an adverse weather light should be used especially in case of wet and rainy roads by dynamically decreasing the glare for oncoming traffic. The implementation of adaptive forward-lighting systems (AFS) into the ECE regulation in 2005 enabled the usage of four adapted light distributions instead of the conventional low beam light distribution. One is an adverse weather light distribution. For two reasons, the possibility of using an adverse weather light has hardly been noticed since then. On one hand, the advantage by reducing the glare for oncoming traffic was quite low for the driver. On the other hand, an adverse weather light which uses the frame described in the ECE 123 required a technical solution implemented only for this light distribution. Until today, new headlamps are tested in good weather conditions, especially in dry summer nights that provide high contrast surroundings. The quality and performance of a headlamp with focus on non homogenities, color effects or the luminous flux can perfectly be rated here. The situation, however, in which the headlamps are faced with the greatest challenge in Northern Europe is more the November with its low-contrast environmental conditions. The following is a description on the adverse weather light approach developed for the Vario Xenon module. Furthermore, the opportunities on the realization of adverse weather light that are given by high resolution headlamps will be discussed. They provide the possibility of implementing the results of the long-time research on adverse weather light to reach the next level of adaptive forward-lighting systems. Adverse weather light has been analyzed in previous research. Out of these empirically investigations several light functions have been developed, which are not yet widely implemented in current headlamp systems. With the introduction of “Class W Modus” by the ECE Regulation 123 a light distribution for wet roads has been allowed by law. Therefore, the examination results of the empirically investigations were used to work out three significant attributes of the adverse weather light:

1. The maximum allowed illuminance of a low beam distribution
2. An increase of cut-off-line to H-5
3. A reduction of the illuminance in the near field

Figure 3.51: Left: back glare caused by fog, Right: glare caused by wet road surface

The first two points concentrate on the decrease of the backscattered light in order to prevent a strong self-glare. In contrast to this the third point deals with the glare reduction of the oncoming traffic due to the reflected light by the wet street, which is realized by a lower luminance level in the near field. A general problem of this adverse weather light function is the compromise which has been made for all adverse weather scenarios (e.g. fog, rain, snow). The introduction of “Class W Modus” was a first and useful step for an adverse weather light, but due to new opportunities in Digital Lighting new functions need to be developed and implemented for several circumstances. Headlamp systems are facing different problems in each weather situation. In scientific works various approaches exist to solve some of them. One approach for the optimization of the drivers view by adjusting the cut-off-line (COL). Due to the empirically examinations dropping the headlamp gradient up to -2% during fog. Furthermore, the luminous flux between the headlamps should be different (difference of 25%). During rain the luminance level of the near field illumination should be decreased. Another approach to deal with the glare reduction of the oncoming traffic by a significant decrease of the illuminance level in the near field up to 8 m in front of the vehicle. A first implementation of a projection module, which could realize AFS functions without a headlamp levelling device, was introduced by HELLA in the Vario Xenon concept. The light shaping is generated by a rotating free-form aperture, enabling the adaptation of the cut off line. However, the reduction of the luminance level in the near field cannot be reached by this module. An additional mechanical aperture was designed in order to decrease the near field illumination. A commercial solution was not provided by this system. As a compromise the decrease of the near field illumination was realized by combining Vario Xenon and the swiveling actuator. In the case of adverse weather light function, the first headlamp was set in the motorway light position in H-5, while the second headlamp with its symmetric COL was swiveled by 15° to the left. Due to this new configuration, the glare level of the oncoming traffic decreased, although a higher illumination range was reached. This function improves the visibility conditions during adverse weather compared to conventional headlamp systems. But still, there is great potential to develop further adverse weather light functions. The development of HD-headlamp technology allows an adaptive adverse weather light, which could dynamically respond to several weather conditions. The degree of realization of the suggestions depends on the solid angle and the resolution of the single systems. Besides the previous mentioned proposals, many other solutions could become reality due to the high resolution, which have been impossible years ago. By the market launch of the HD Matrix 84 Module of Mercedes in 2014, a system was introduced, which could be dynamically varying the light distribution by switching on and off single light sources. This means - for the first time - the AFS function is not realized with mechanical components. In addition, this series headlamp has the potential to statically modify the high and the low beam in order to realize each adverse weather light function suited to all the different weather conditions. These functions could be implemented according to different light distributions for various weather conditions. However, this module allows a limited resolution with a minimum of 1.2° x 1.2°. Current discussions of high resolution headlamps consider systems with an angle resolution of 0.2°. Using a DMD based solution the resolution could be decreased down to 0.02°. Hence, in order to reduce the reflection by wet roads, it could be possible to realize a headlamp system, which responds to oncoming traffic with a spatially adapted light distribution. This headlamp module requires a camera system as already introduced in 2010 with the glare-free high beam. Therefore, using the combination of high resolution headlamps, the camera based system and appropriate operating rules, an adaptive real time adverse weather light could be implemented. Thus, the technical solution is already available, but the operating rules and its mode of action are still under development. To further test this new adverse weather light, an “HD Evaluation Platform” with a resolution of 0.02° and an illuminance of around 100 lx is used. Such small solid angles allow a variation of the resolution, so that different technologies (with a lower resolution) could be imitated and investigated without changing the light module. Besides the position of the oncoming traffic, a real time high resolution adverse weather light could also consider the different reflectivity levels of the road surface. Depending on the back scattered light, the luminous flux of the headlamp could be decreased in the most important glare area in the light distribution. In contrast to this, the illumination in the non-glare areas could be increased to achieve a better field of view. Another point that needs to be investigated is the contrast optimization at the roadside. Using a Vario Xenon module the left roadside was illuminated higher, which could increase the recognition distances of objects in several situations. Due to the HD headlamps the opportunity arises to optimize the contrast on the roadsides by the collected data of the camera system. The investigations for such a dynamical increase of the contrast at the roadsides for different situation have not been completed yet. On the following are presented the first strategies of adverse weather light functions realized by HD Systems. They are illustrated by photographs that have been taken in the light tunnel and on a rural road to demonstrate the basic principle. The first strategy is the reduction of the luminous flux in the near field as it is shown in Figure 3.52 right. Compared to the original light distribution (Fig 3.52, left), there is no reduction in the detection distances of objects on the roadside. In case of snowfall or fog, this strategy reduces the self-glare for the driver. It also reduces the glare for oncoming traffic caused by the forward reflection of the street in case of rain.

Figure 3.52: Flux reduction to reduce self glare of the driver

This concept is quite similar to the strategy that shifts the beginning of the light distribution up to 8 m in front of the car. To realize this strategy, a high resolution is not needed. Instead, a separated illumination of the near field is necessary. This can be realized by using an adaptive headlamp providing a wide solid angle. Also, systems that illuminate the near field by the usage of a separate module can be used if dimming is possible. A lifting of the light distribution by using the automatic levelling control also affects a rising of the COL and can only be used as a solution when the COL is descended adaptively. The next strategy is the reduction of luminous flux in the far field (of a low beam distribution) as presented in Figure 3.53. In case of adverse weather conditions an illuminance of those regions is not necessary. This approach effects a reduction of the self-glare of the driver especially in case of snow and fog. This strategy requires an adaptive headlamp that achieves a reduction of the luminous flux below the COL. A high-resolution module is not needed.

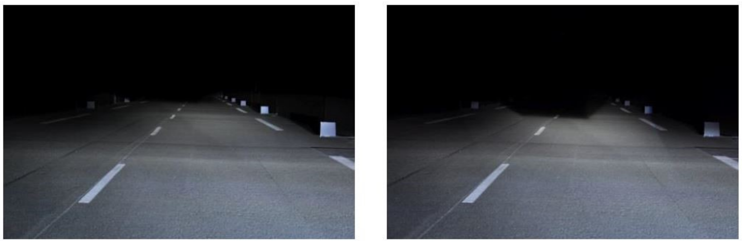


Figure 3.53: Reduction of luminous flux in the far field

Another strategy is the dynamic street shading in direction to the oncoming traffic underneath the cut off line, which could be used especially on wet and rainy roads. In this case, the oncoming traffic can be glared by the forward reflection of the wet road surface. Similar to the concept of the glare-free high beam, also the light distribution below the COL can be adapted to reduce this glaring (Figure 3.54). Here, appropriate sensors and actuators are needed. The high resolution adaptive area extends beyond the high beam area to the near field. Depending on the channel width and the tolerated shading area around the oncoming traffic, different high definition resolutions are needed in the vertical opening angle of the light module. The HD 84 Matrix Module with its horizontal resolution of 1.2° per pixel is the highest resolution headlamp on the market today. It is also the first system that achieves an adaptive shading of the low beam distribution. The LCD technology providing about 30,000 pixels per headlamp increases the horizontal and vertical resolution which leads to an even finer shading down to 0.2° per pixel. Furthermore, symbol projection could play an important role when adverse weather light functions are discussed. In case of Figure 3.55, a simple slide projector could be used to project different symbols like a snowflake on the street in case of dark surroundings. As soon as the number of different slices increases, a dynamic high resolution projection system is needed. A projection of the current temperature could be an example. Another example could be the realization of animated symbols to e.g. increase the driver's attention. Digital Micro Mirrors Devices (DMD) providing more than a million pixels could be used for such highresolution projection systems. Focusing on symbol projection in the near field, the huge solid angle of the LCD technology is not needed.

Figure 3.54: Dynamic street shading in direction to the oncoming traffic

Figure 3.55: Symbol projection on the road

The last strategy is the optical lane assist. The simplest way to mark the road course would be a static projection module which can be swiveled. Fitting the light tube to the bending of a curve, the optical lane assist strategy turns out to be the most dynamic one. Here, a high resolution over the entire light distribution area is necessary. In case of fog or snowcapped roads, the “light tubes” could be used to mark the way for the driver to give orientation and to improve driving performance (Figure 3.56).

Figure 3.56: Projection of ”light tubes” on the road

Obviously, the optical lane assist requires high-precision map materials. Dynamic arrows (Figure 3.57) could additionally transport further information assisting the driver fulfilling his longitudinal driving task.

Figure 3.57: Dynamic arrow projection on the road

High resolution headlamps and camera based systems represent a useful technological basis for realizing adverse weather light functions. Besides the aim in this field of studies, the first results of investigations using a “HD Evaluation Platform” could have been presented. The next step is to find appropriate operation rules to realize an adaptive adverse weather light and to define a sufficient resolution for these headlamp modules. A special task is the contrast optimization in the roadside area. In recent years, the development of new headlamp systems highly improved the visibility for the driver at normal weather conditions during night time. Even the oncoming traffic is not influenced by any high beam due to glare-free high beam technology. But unfortunately, adverse weather is very common (especially in the northern part of Europe). Current headlamps are still not optimized for these weather conditions. Properties which are beneficial for normal weather conditions (e.g. a high luminous flux) could influence the driver, when the weather is changing. Headlamps could easily reduce the self-glare (e.g. for snow or fog) by decrease the light in the near field. Modern headlamp technologies support even more complex functions due to higher resolutions. These new adverse weather light functions need to be implemented successive. When the first high resolution headlamps get into market in 2020, the step for the realization of an adverse weather light is the implementation of an appropriate software with a sensor based algorithm. This introduction of a new adverse weather light could help to enhance visibility and allow more comfortable driving through different weather conditions. Thus, an implementation of the new functions would encourage the end customer to invest in this new technology.

3.9 Cost reduction on full led headlamps [13]

In 2016 Renault set an important target for the 2018. This target was to have as final result a full LEDs headlamp with the same price level as an halogen headlamp.

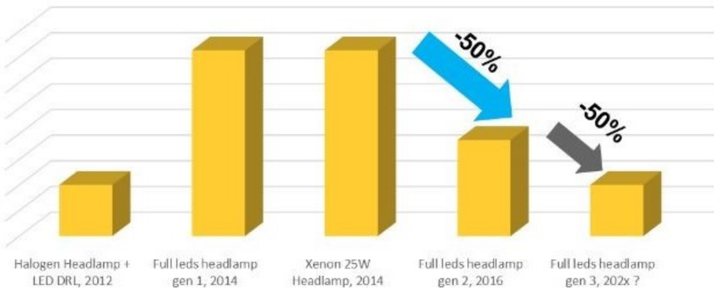


Figure 3.58: Headlamp cost reduction

With current full LEDs solution, Renault has a very cost competitive solution and sell a lot of cars with full LEDs headlamp, not only for premium customers but for more than 50% of the Captur customers for example. Renault is able to propose today, in Europe, full LEDs headlamp on all the B, C and D-segments.

Figure 3.59: Full LED headlamps on C&D segments

Renault strategy is to continue the deployment of full LEDs headlamp for 2 main reasons:

1. Styling attraction: Thanks to full LEDs headlamp is possible to reduce the height of the headlamp (if there is no halogen version). Height can be reduced from 200mm to 150mm or even 100mm. In parallel, depth can be reduced around 50mm that means 50mm length reduction of the car.

2. CO2 saving: With halogen headlamp, power consumption is around 150W when Low beam is ON. With LED headlamp, power consumption can be reduced by 2. Current value is between 40 and 60W depending of the lighting performance and the optical efficiency of the optical system (the higher the reflector is, the more efficient is the optical system). Saving is around 100W that can be translated in fuel saving for ICE, or battery autonomy for EV vehicles.

To be able to work on standardization of full LEDs headlamp, two different aspects must be considered:

- Styling with emotional design
- Cost reduction

In the following the focus will be on cost reduction. Cost distribution on the headlamp generally is as follows :

- 10% of headlamp price due to LED ECU (driver)
- 10% of headlamp price due to height sensor system
- 35% of headlamp price due to optical module

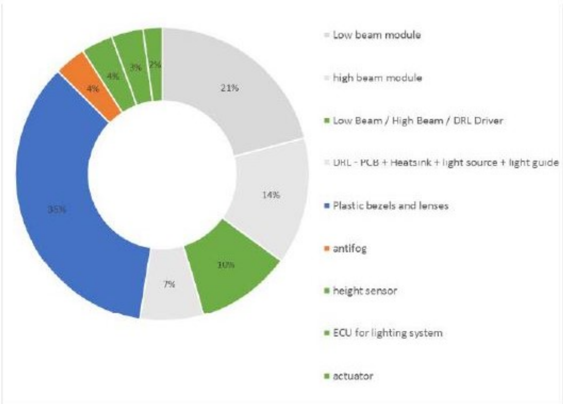


Figure 3.60: Headlamp cost roadmap shown in 2016 vision congress

For generation 3, the height sensor system was not introduced. This was possible due to regulation evolution with possibility to have standard levelling system if the car has headlamp with less than 2000lm. About LED ECU driver, there is an ECU with Renault and Nissan with 13 cars in mass production, 11 in developments and others in predevelopment, included Dacia, Lada and Mitsubishi brand. Thanks to standardization, it was possible to share R&D cost and also to optimize production capacities in supplier plants. This LED ECU is also very well optimized with:

- Only one common buck/boost for Low Beam and High Beam
- One common Bin resistor for Low beam and High Beam
- One common thermal sensor (NTC) for low beam and high beam

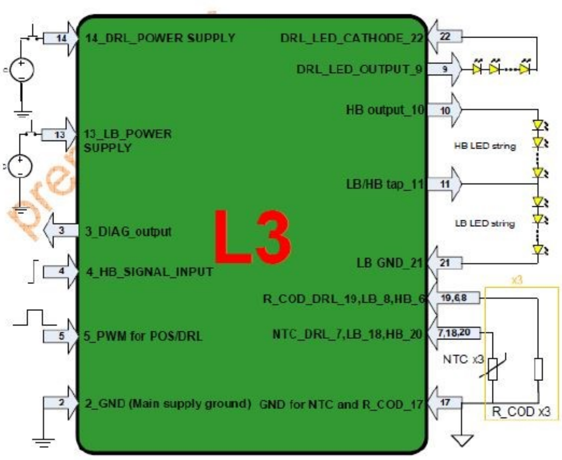


Figure 3.61: ECU diagram for full LED headlamp

This ECU is implemented on a lot of cars thanks to the definition of the following parameters :

- current adaptation
- voltage adaptation depending on the number of leds, with a maximum power of 54W

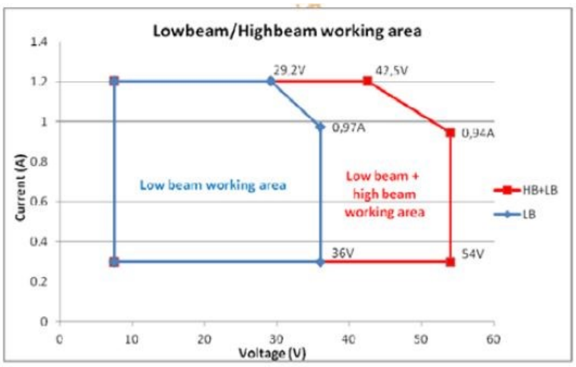


Figure 3.62: ECU working are graphic

Between generation 2 and generation 3, there was improvement on LEDs side, PCB side and thermal management optimization. These 3 components represents more than 50% of the price of the optical module.

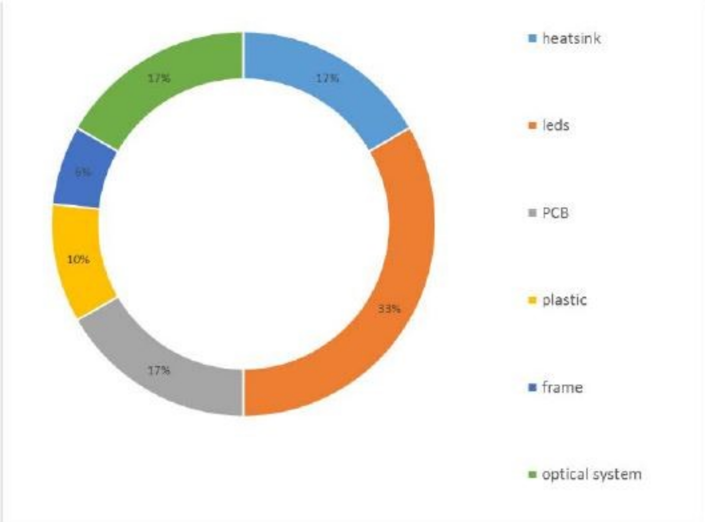


Figure 3.63: Optical module cost roadmap shown in 2016 Vision Congress

Firstly, by increasing LEDs flux, with higher current and higher bin flux. Result is 30% flux increasing.

	current (mA)	flux (lm) / led	number of leds	junction temperature
low beam led Gen1	800	200	8	120
low beam led Gen2	1000	270	5	130
low beam led Gen3	1200	360	4	100
high beam led Gen1	800	200	4	120
high beam led Gen2	1000	270	4	130
high beam led Gen3	1200	360	2	100

Figure 3.64: Evolution of LED flux in optical module between gen1, 2 and 3

Secondly, PCB dimension optimization in order to have more PCBs on the same panel in EMS supplier. Result is 30% PCB size reduction

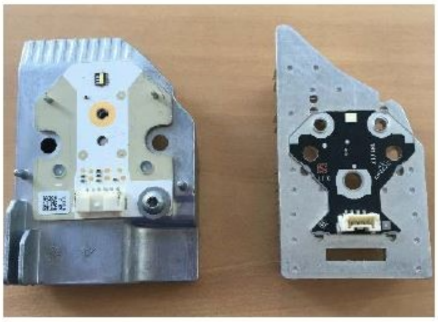


Figure 3.65: Evolution of PCB size between gen2 and gen3

Thirdly, optimizing heatsink thermal dissipation. Result is a weight saving around 30%, with better thermal dissipation than generation 2, thanks to :

- Rth LED improvement,
- Rth PCB improvement,
- Better heatsink design thanks to better thermal simulation with FloEFD software.

Figure 3.66: Evolution of heatsink weight between gen2 and gen3

Last but not least, drastically reduction of the price of optical module, by changing the paradigm : LED module (inside Optical module) would not be imposed by Tier1 supplier but would be imposed by the Car maker. Renault has defined the technical characteristics (especially mechanical and electrical interfaces) and has imposed the LED module to all the tier1 suppliers. By applying this policy Renault can increase standardization. A complete family of LED module has been developed:

- with 2, 3 and 4 leds versions
- with or without Bin resistor and thermal sensor (mother and sister LED module). To have very good performance, Renault work a lot on :
  - LED flux variation between 2 bins
  - LED, PCB and reflector geometrical deviation.

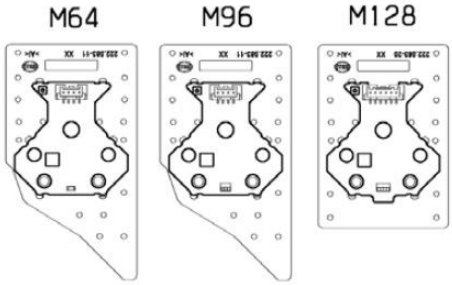


Figure 3.67: PCB optimization

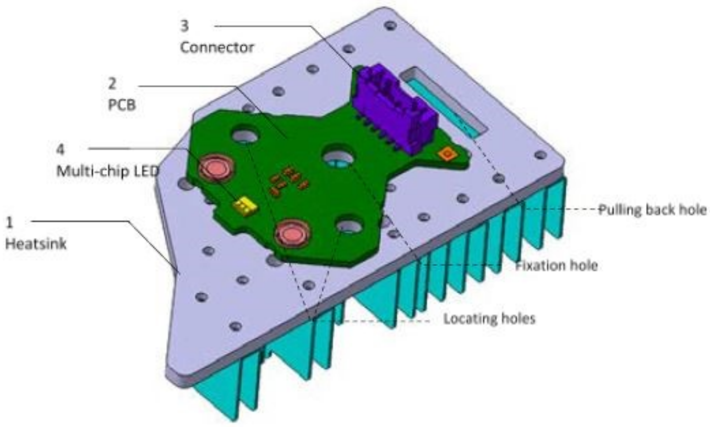


Figure 3.68: PCB and heatsink assembly

Lighting performance of this generation 3 is better than generation 2 :

- Low beam flux +20%
- Low beam width improved +20%
- High beam range and high beam width increased in spite of LED number reduction (from 4 leds to 2 leds between gen2 and gen3)

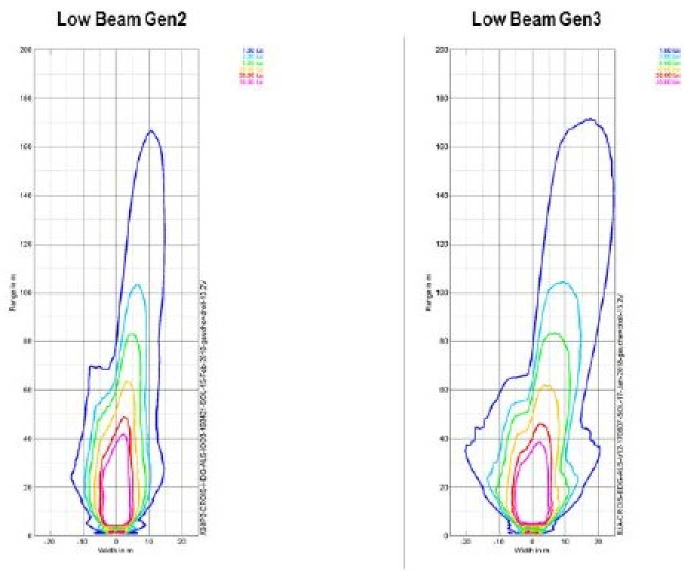


Figure 3.69: Low beam improvement

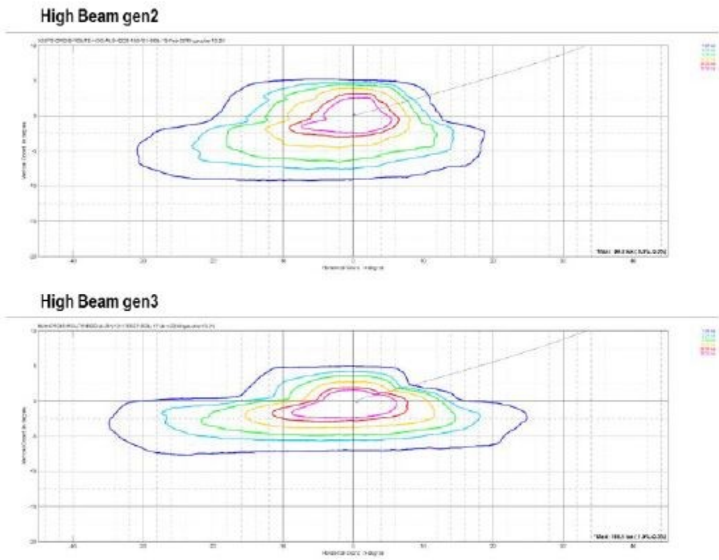


Figure 3.70: High beam isolux @25m

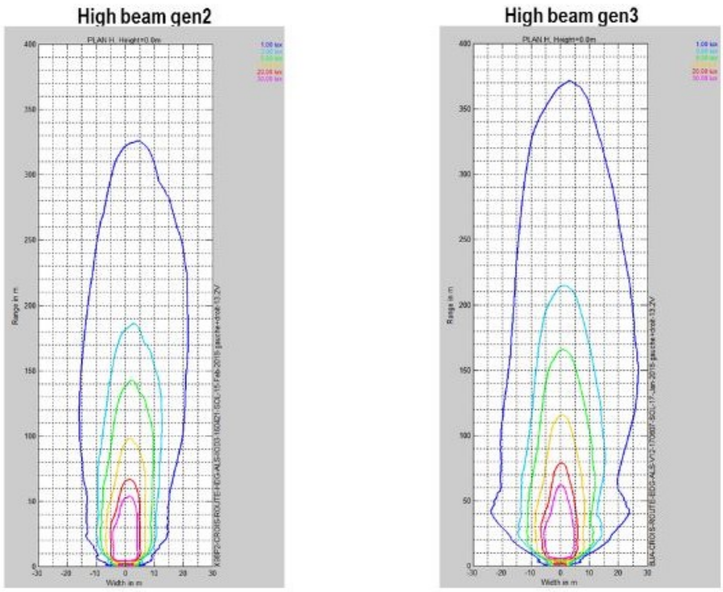


Figure 3.71: High beam bird view

To be able to achieve this performance, low beam cut off line is moved up to +1,3% when high beam is switched ON. The range were increased from 180m to 210m (3 lux criteria) and the width (especially at 100m) With generation 3, there was an improvement of lighting performance with reduced cost. Halogen target price is not far and the improvement will go on. Thanks to this work, Renault is able to propose full LEDs headlamp with very high take rate on B, C and D segment and soon on A segment also. One idea of improvement could be the usage of exchangeable LED modules. If that is feasible cheaper LED could be used, LED at higher junction temperature could be used (heatsink size could be reduced or even heatsink could be cancelled) and weight can be reduced.

3.10 Prototype of high definition headlamp [14]

The presented headlamp concept based on Micro Mirror Device technology as a central enabling element offers high definition light projection to display and potentially animate new visual information on the road (use as advanced information low beam) addressing the driver and other road users. Projecting information as maneuver communication in advance will mean the driver and other road users can both see the driver's intention and therefore reduces risks. For example, during lane changes. Further up the road, careful adjustment of the field of view covered by high resolution functionality, eye strain will be reduced by the smooth transition of segment dimming using grey scale functions. Improved eye focus will be on intentionally set hotspots (e.g. moveable highlighting or marking light). The central high definition zone is supported by a next generation Pixel/ Matrix with reduced height as well as a foreground module to complete basic illumination. The latter is part of a design stripe, built in combination with the animated (also total internal reflection optics) signaling elements. All together this next generation HD headlamp with new features and styling opportunities, a brilliant, catchy appearance is realized nevertheless emphasizing the needs of a sporty driver. ZKW, manufacturer of high-resolution lighting systems, has yet another technology in the starting blocks practically offering optimum lighting along with many new functions. It represents a major step towards creating systems that do much more than just generate illumination for the driver. This new technology will be tested as a near-series prototype vehicle alongside and together with Jaguar Land Rover in order to explore the new possibilities it is offering in practice and to thoroughly understand implications for specification and integration in the vehicle network.

General trend towards high-resolution headlight systems

From the automobile manufacturer's point of view, there are two trends which, while they might seem contradictory, are currently in vogue: On one hand, the height of headlights will decrease in the future. On the other hand, there also is a clear trend towards "actuator-free electronic high-tech headlights." Progressive digitalization in vehicles together with evolving sophisticated lighting technologies require and simultaneously inspire new lighting functionalities that go beyond the simple need for lighting. Information for the driver, or even driver guidance with targeted lighting will be possible in future vehicle generations and will be necessary in increasingly complex traffic. In the meantime however, today's cars already adjust light distribution in front of the vehicle automatically and draw the driver's attention to impending dangers in order to increase active and passive safety on the road.

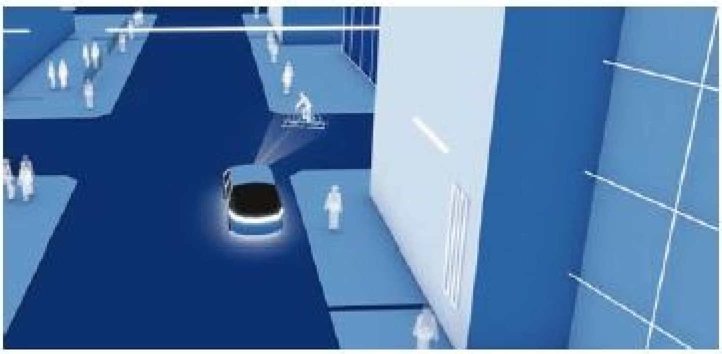


Figure 3.72: Pedestrian vehicle integration, marking light

ZKW identifies and develops technologies for these kinds of scenarios. The days of the "mechanical product" are long gone and the "mechatronic / electronic product" with high imaging resolution is now a reality. High-resolution projection technologies help create the functions needed to follow these trends. Deducing from the consumer electronics sector there are four high-resolution projector systems available to be conceivably transferred to smart headlamps. One of these is LCD, which uses liquid crystal in a transmissive arrangement as the imaging element. LCoS technology uses a similar structure, with a reflective liquid crystal element. Laser scanning technologies, which use the laser beam as a writing element for image generation are already in use on a small scale. Finally, DLP technology from Texas Instruments is another option and currently the only one suitable for use in automotive environments. Which technology will prevail in the end is not yet clear. When comparing all of the possibilities, there are many advantages and disadvantages of the respective solutions to be considered. As mentioned, nowadays DLP has the biggest advantage as it is already suitable for use in headlights. Consequently the near-series prototype presented in the Range Rover Sport hereby is a DLP headlight module.

Potential of high-resolution headlight systems

The vision of a networked, digitalized vehicle is within reach. It will offer more safety on the road and require a general reorganisation of lighting and electronic components, as well as automated and autonomous driving functions. In the future, headlight systems with automatic, variable total light distribution will cover a large part of the lighting market and lighting will be networked with the sensors already in the vehicle to create a smooth transition from lighting tools to information and assistance tools. For the driver, it is important to take the right steps towards a forward-thinking philosophy and a "cognitive product" concept by developing headlights that augment human visual perception. Such cognitive products must incorporate integrated perceptual assessment and decision-making capabilities and set new standards for handling these changing structures.

Figure 3.73: Lines projection on the road

New functions, such as forward projections, are necessary to achieve these goals. These projections can assist the driver in critical situations and help him to make necessary decisions. In the twilight of information systems, heads-up displays and high resolution projection modules being able to project information onto the road, there are two ways that headlight solutions are helping new generation vehicles to interact with the outside world. Especially during night driving, where the driver's visibility and recognition rate are much lower than during day and the risk of accidents increases significantly, targeted information greatly improves the driver's sense of safety.

Figure 3.74: Lines projection on the road helpful during glaring situations

High-resolution headlight systems can illuminate the road in front of the vehicle by directing targeted light towards critical areas without dazzling other road users, showing all the information the driver needs without forcing them to take their eyes off the road in a critical situation. Auxiliary lines and symbols, combined with consciously controlled contrast in the lighting patterns can help drivers in critical situations. These features not only provide high-quality assistance to drivers, but can even act as management tools. Targeted control of the driver's line of sight using dynamic brightness adjustment in light distribution improves situational visibility at night. Also important are the general improvements in illumination and light distribution that these high resolution headlight systems offer. Cornering lamps, which have been unchanged for years, will essentially remain the same. They retain their analog, continuous character when panning without mechanical moving parts.

Figure 3.75: Symbol projection on the road helpful for navigation

High-resolution, glare-free, high beams increase safety. They allow the shadowed area to be located very closely to the object to be masked. So close that not even the driver notices the masking. This depends, of course, on the tolerances and reaction time in the overall system. The network camera bus system, headlight ECU and adjustment tolerances set the limit. In dynamic situations, on the other hand, all effects resulting from lower resolutions are avoided. For example, even initial exploratory night driving studies have shown that more turbulent ADB systems with lower resolutions influence viewing behavior, and thus visual attention which cannot be compensated for by higher-resolution systems alone. In the future, this will be one potential application for consciously controlled lighting patterns and some of the topics discussed above.

Figure 3.76: High definition headlamp performance increase

The strategic development initiative for high resolution headlight technologies shows the company's clear commitment to a "pioneering lighting system" for more safety. ZKW has established itself as a pioneer in an extremely competitive environment by pursuing several developments in this sector. Due to the large amount of development work required, the diverse, competing and highly complex technology involved as well as resulting target products, there are high risks – both related to technical implementation of the products and commercial matters. The benefit to future drivers is clearly emphasized as the key strategic focus for development, in order to avoid getting tied to often very short-term or changeable immediate ideas. In summary, the focus of lighting technology is shifting from improved viewing to improved perception (active/passive). Front lights are evolving from driver-oriented light sources to machine oriented components that, in the future, will impact the entire vehicle. In contrast to OEMs' focus on using luxury class equipment instead of increasing traffic safety, these developments clearly show there is an interest in broad use across all vehicle classes.

Imaging using Digital Light Processing

This technological approach is based on Texas Instruments' well-known DLP technology platform. In the core light forming MEMS element, many micrometer-sized tilting mirrors are arranged in an array. Each mirror can be tilted and held in two end positions. Light is transmitted from the light source either through the imaging optics or directed into an absorber, depending on whether the individual micro-mirror is in one position or the other. If the light propagates through the lens to the outside, it creates a bright spot of light on the road. When the light is directed into the absorber, no light is directed to the relevant location. In this way the mirror array – DLP chip - builds up an image and projects it through the lens onto the road. The fast tilting movements of individual mirrors - multiple kHz - allow intermediate values (gray values) to be represented and very fast image sequences to be created. Indeed the DLP chip itself is a highly compact component, but since it is part of a more complex system that has to deliver the expected exposure values, the light source is subject to exceptionally high demands. On the one hand, enough light must be provided to sufficiently illuminate the specific area. On the other hand, the source must not exceed a certain magnitude nevertheless allowing sufficiently high contrast without reduced efficiency. A specific construction feature of DLP technology is the acceptance angle within the optical path of MEMS illumination, which must not be exceeded. Otherwise, the contrast values in the illustrated light image will no longer meet legal requirements for a glare free headlight system. The module's imaging optics also represent a well optimized compromise. Efficiency, size and weight must correspond to the usual parameters for headlight construction. Because of this, it is not possible to provide the image quality customary in consumer video projectors which include more than 10 optical lenses. Transferring this to car headlights would exceed all weight and space specifications while offering extremely poor system efficiency. New control electronics also had to be developed. It is no longer possible to control each pixel individually as it is the case with matrix systems. The controller board contains the usual repeaters from the vehicle bus and calculates the corresponding DLP image by means of a graphics engine. The hereby presented solution, which is already close to market readiness, was used to drive the development issues regarding the usage of specially adapted components as well as technological validation in general. Due to brisk customer interest in the Gen1.5 DMD module, initial preliminary tests for B-sample qualification have already been conducted on electronics and modules level for the first version of ZKW DLP 1.0, while a specially adapted Gen2.0 module (2:1 aspect ratio) was being developed concurrently to offer simplified optics and increased light output. This concept is being developed for series production alongside Jaguar Land Rover and therefore will be used in JLR vehicles for the first time in high volume.

Figure 3.77: High definition module prototype

Figure 3.78: Prototype vehicle equiped with high definition headlamp

The purpose of this mockup is to demonstrate and evaluate new features with DLP technology. Therefore a prototype headlamp was built and fitted into this serial vehicle (L494 MY18: Range Rover Sport). The serial camera acts as main sensor. The lighting and feature control is performed in a separate control unit. Data from chassis CAN and the camera are merged by a separate gateway. Before reaching series maturity, specific vehicle body influences will be tested and demonstrated using this vehicle body in the Range Rover Sport. Non-series parts were deliberately omitted in order to obtain results as close to reality as possible. As indicated before, perfected imaging results equivalent to the popular consumer beamer are not the goal as they would not be usable for the intended series production headlight. Instead, the focus is on analyzing realistic interaction with other light modules in the headlight, coordinating algorithms between camera and headlight control, determining the type and position of possible symbols in front of the vehicle depending on the driver's position and viewing angle and much more.

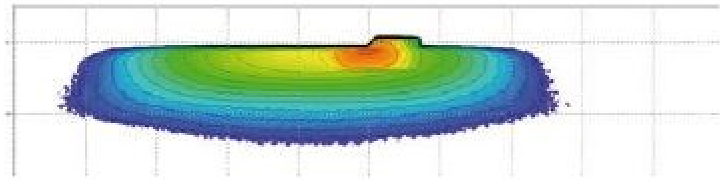


Figure 3.79: Low beam light distribution with DLP module

The entire system has already advanced so far in its design that the designers are certain its light distribution will be legally compliant. Especially in glare-free high beams, reaching the maximum permitted stray light values pose a special challenge and extreme situations in which a fail-safe module is necessary must be investigated. To get full legal lighting functions different modules were fitted into the prototype lamp. The DLP Module offers a meaningful field of view in horizontal and vertical and supports dynamic features in low- and high beam. The Pixel module with 17 segments overlaps the DLP in the center area and gives a high beam width of +/- 27°. The 9 Foreground lenses give a base beam of +/-31°. Similar technology is used for the 8 signaling lenses for position light, daytime running light and the animated turn indicator. The static bending light is done with a LED reflector solution.

Figure 3.80: Prototype headlamp Range Rover Sport

Figure 3.81: Prototype headlamp Range Rover Sport

The DLP module uses TI 2nd generation DMD device with addressable 1.3MPixels (mirrors). The module is powered with high power LEDs. The DLP module includes a control unit, LED-driver and cooling system. The main lighting functions are achieved by merging the output of the DLP-, Pixel-HB- and the foreground module. Figure 3.82 shows the overlap of the 3 modules. The low beam kink is done with the DLP.

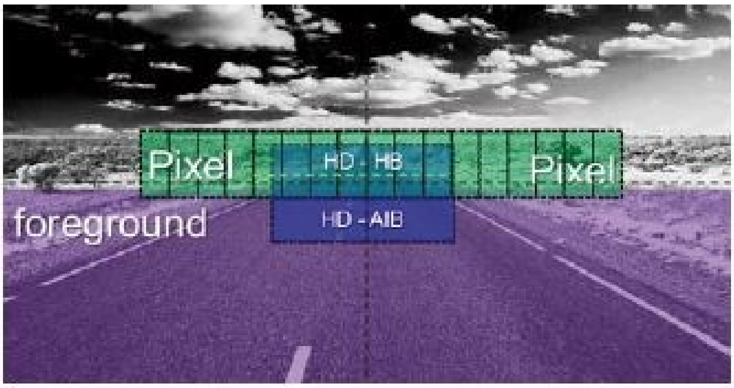


Figure 3.82: Prototype light distribution

For ADB the Pixel and the DLP light distributions are overlapped. With the high resolution from the DLP it is possible to project precise tunnels close to oncoming or preceding vehicles. Due to the high vertical resolution the vertical shadow in front of a vehicle, know from common Pixel systems disappears. The DLP with its high resolution offers new lighting features which needs to be evaluated and approved by legal authorities in near future. Precise and smooth signpost dimming, predictive AFS based on interactive map and environment data, projection of warnings, guidance beam and marking pedestrians are some safety related features. Care must be taken to ensure that fancy features such as welcome/shutdown effects with animated projections and projection of navigation information like turn signals don't lead to distraction or discomfort of other road users.

3.11 Headlamp with DMD technology [15]

The worldwide first high resolution series headlamps with DMD (digital mirroring device) technology are in production for the Mercedes-Maybach S-Class. The new freedom for the creation of light distributions offers not only a significant performance improvement of the existing lighting functions such as AFS-low beam and camera controlled ADB functions, but also opens the opportunity for new lighting functions like guidelines and symbol-projection on the road. This leads to a new level of safety and comfort during night time driving. DMD technology has been discussed for a long time as one of the most promising technologies for high resolution headlamps. In the last two years the decisive breakthrough occurred: The first presentation of a showcar with Digital Light in 2016 was followed by the announcement of the first series project with DMD technology in a Mercedes- Maybach SClass, which was presented on the Genfer Autosalon 2018. With this first project (headlamp see fig.3.83) the way is paved for the market penetration in the next years.

Figure 3.83: Mercedes Maybach S-Class, First serial project with DMD technology

In the following will be given insight into the technological realization of the DMD module of the first series headlamp with DMD technology. The generation of light distributions, which has to follow a completely new approach, are described and illustrated in principle and various application examples are given. The technical realization of the DMD module is described with special emphasis on the DMD chip, the DMD-ECU, the optical concept, the thermal concept, the optical performance and the optical image quality.

DMD Chip

The key component of the module is the DMD chip from Texas Instruments (TI). Is used the automotive qualified 0.55" DMD chip of the Gen. 2, DLP5531. The package is quite compact with outer dimensions of 32 mm x 22 mm and a height of roughly 3 mm (see fig. 3.84). The micromirror array contains 1.3 megapixels. The mirrors have an edge size of 7.6μm each. They are arranged in a diagonal 1152 x 1152 pattern, covering an active area of 12.4 mm x 6.2 mm with 2:1 aspect ratio. Always two neighboured mirrors are addressable, such that the effective pixel number amounts to 1152 x 576. Each mirror has only two defined states: on or off. Flipping between these two states occurs in the kHz range. By the on-off ratio different grey scale values can be realized. The bit depth of the grey scale is 8 bit, so 256 grey scale values can be realized.

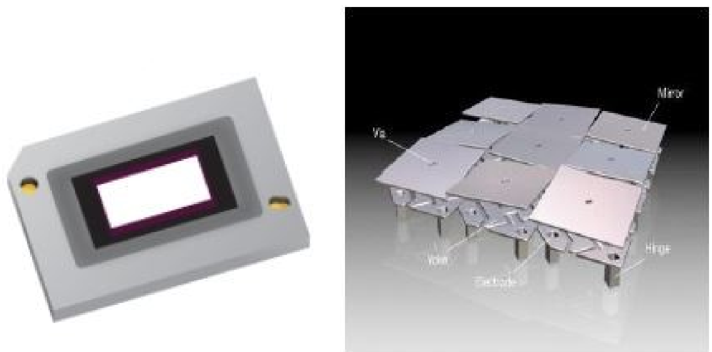


Figure 3.84: DMD chip

DMD ecu

The DMD chip is connected to the DMD-ECU that contains amongst others a deserializer and the two further components of the TI chip set, the processor DLPC230 and the companion ASIC TPS99000. A simplified block diagram of the data processing is shown in fig. 3.85. At a higher instance, e.g. the main headlamp ECU, an image is calculated by a graphic unit. The calculated image data are provided to the DMD-ECU by a serial data bus, the HSVL (high speed video link). The incoming serial data stream is split again into a parallel data bus by the deserializer IC and then forwarded to the DLPC230. This TI processor controls the DMD chip via a specific, complex interface to display the image.

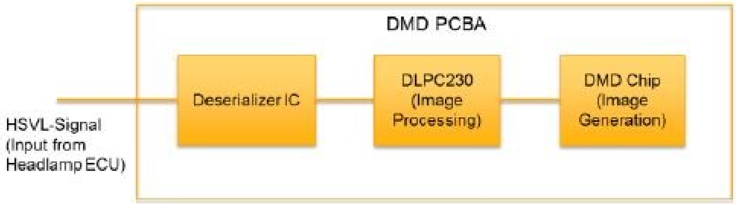


Figure 3.85: Block diagram of the data processing

To manage the proper functionality under usual automotive conditions like varying temperature and supply voltage, several actions have to be done in addition to the image processing. For that reason, further structures with a communication interface (CAN) to the ECU(s) in front of the DMD-ECU, a microcontroller, the TI ASIC TPS99000 and an internal SPI communication to the DLPC230 processor are present as well. Parameters which are controlled are e.g. the DMD temperature, the DMD duty cycle ("Illumination Bin") and the synchronization of the illuminating LEDs with the DMD Chip.

Figure 3.86: DMD module

Optical Concept

With this DMD chip as key component, a projector which is suited for headlamp application is build. The requirements are very strong: small, efficient, robust and cost-effective at the same time. The DMD module as applied in the first serial application is depicted in fig.3.86. Much optimization effort was necessary to combine the complexity of the DMD technology with the high requirements on construction space. As light source were used three high current LEDs with 2 mm^2 chip area each. The light of each LED is collimated by a primary optics and then directed onto a reflector. The reflector is designed such that it illuminates the DMD very homogeneously. The DMD mirrors are in the focus of the imaging system. If the mirrors are in the on-state, the light may pass through the imaging system. This objective is made of three lenses to assure of a good image quality. The active area of the outer lens is about 50 width and 30 mm height. These small dimensions in combination with PMMA as lens material may be quite attractive for the headlamp design: Beyond the active area the design of the lens can be styled in various ways.

Thermal concept

The thermal concept of the DMD module is very challenging. The main thermal power contribution comes from the high current LEDs which can be driven up to 6 A according to the datasheet. Additional heat sources are the dissipation loss of the DMD-ECU and light absorption. In contrast, the DMD chip is quite sensitive to heat. According to the datasheet the maximum operating array temperature is 105°C. This issue were solved by using an efficient active cooling system in combination with a Peltier element for the DMD. This Peltier element has to be operated in an intelligent manner in order to bring only a minimum of additional heat into the system. Furthermore, the operating point of the module has to be optimized. For a specific driving condition and a specific thermal environment, the LED current and the DMD duty cycle have to be chosen very carefully to maximize the light output.

Optical performance

The optical performance of the module is strongly influenced by the type of the objective. In the first series application an objective that projects a field with 14° horizontal and 7° vertical extension were used. A very homogeneously illuminated field with a slight intensity decrease at the edges were generated. The luminous flux in the whole field is approximately 1000 lm with a maximum above 90 lx. These performance values refer to a stand-alone module at 25°C after thermal stabilization with consideration of a typical outer lens. The characteristics of the illuminated field can be seen in figure 3.87.

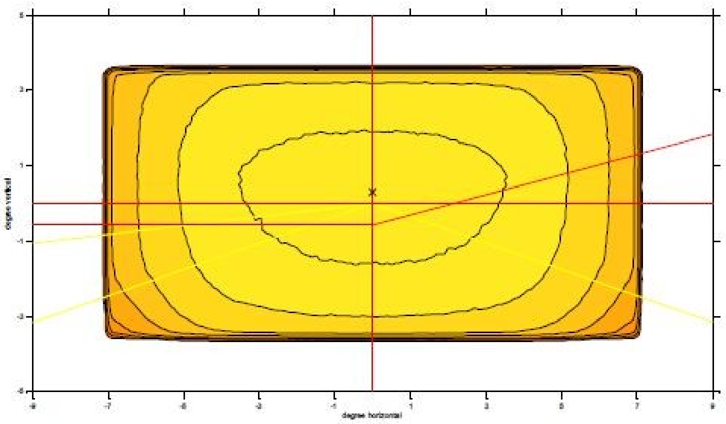


Figure 3.87: Illuminated field

Optical image quality

The DMD system is completely different to all customary automotive lighting systems, as it is both very flexible concerning the projected object and characterized by high resolution. Therefore, new methods for the characterization of the optical system quality are necessary. A method has to be found which does not characterize specific light distributions but the optical imaging quality in general. One very common method of imaging optics for the description of the image quality is the modulation transfer function (MTF). It describes the ratio between the image contrast and the object contrast in dependence of the spatial frequency. The contrast is defined as the Michelson contrast: Contrast=I_{max}-I_{min} /I_{max}+I_{min} with Imax and Imin being the maximum and minimum illuminances. The spatial frequencies may be given by line pairs (bright/dark) per degree. If the object contrast is 1 for all spatial frequency – which is e.g. the case by bright/dark line pairs as objects – the MTF is simply reduced to the image contrast in dependence of the spatial frequency. One approach for the experimental characterization of the optical system consists in projecting pictures with specific numbers of bright and dark line pairs (objects) with the DMD module and measuring and analyzing the resulting images. An example for a line pair of 1.1 line pairs/degree is shown in fig. 3.88, upper picture, and an example for a line pair of 5.1 line pairs/degree is shown in fig 3.88, lower picture.

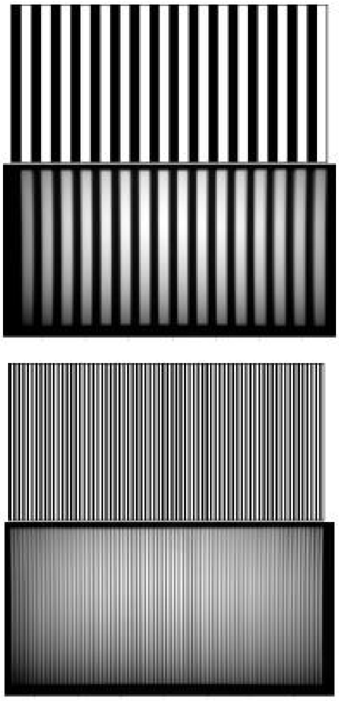


Figure 3.88: Pictures with line pairs as input (object) and output (image) of the DMD module. 1.1 line pair/degree (upper picture) and 5.1 line pairs/degree (lower picture)

These pictures show that the contrast is approximately 1 for 1.1 line pairs per degree (upper figure) and lower for 5.1 line pairs /degree. By calculating the contrast for a certain area of the picture and by doing so for various pictures with different line pairs/degree, the MTF can be obtained. A curve similar to that of fig. 3.89 is obtained, where the MTF measurement for an idealized module is depicted. For those measurements one has to consider general limitations of the measurement equipment, according to the Nyquist theorem. The theoretical limit in our application is given by the ratio between the number of DMD mirrors and the spatial extension, so by the ratio 1152 / 14 ° = 82 lines per degree or 41 line pairs per degree, the reciprocal being the resolution (0.01°).

Generation of Light Distributions

High-resolution headlamps allow for a completely new way of generating light distributions. No longer are we bound to fixed light distributions for certain driving situations. It is now possible to adapt the light distribution to the surrounding of the car in real time. Consequently, one could consider it as the fourth generation of light generation after the following three generations: first, the creation of the light distribution by the scattering outer lens, second the free form reflection and projection systems, third, electronically controllable matrix systems up to about hundred pixels. In this section a general overview of the challenges for creating light distributions for high resolution systems is given.

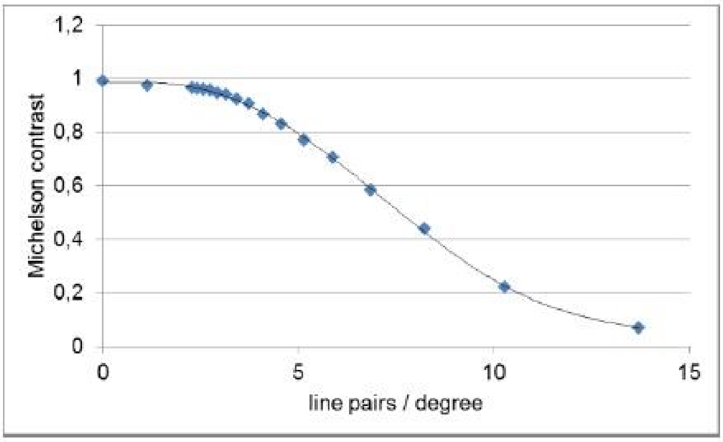


Figure 3.89: MTF function for an idealized module

General concepts

From a technical point of view the control of the light pattern is performed by sending pictures to the DMD. A high resolution of up to 1152 x 576 pixels allows for illuminating a given scene with a yet unachieved precision. Moreover a refresh frequency of 60 Hz on the DMD makes the beam pattern highly dynamic. While this concept allows for a whole wealth of applications, a key challenge is the generation of the image which ideally illuminates the corresponding driving situation. For this purpose, two main points need to be addressed:

- The flexibility of the light distribution. This means that illuminances for each pixel may vary due to changes in the environment of the car. Nevertheless, independent of the driving situation, the light distribution always has to be smooth, homogeneous, possibly also adapted to other modules, and moreover legal.
- Real-time rendering of the picture. Since the picture has to be calculated in real time on the headlamp, the underlying algorithms need to be sufficiently fast such that no frame drop occurs. Moreover, data rates and memory consumption need to be accounted for.

These two points are contradicting in the sense that the demanded flexibility increases the computational complexity which is not desirable since the picture has to be rendered in real time. To overcome this issue, approaches are needed which perfectly balance these two main requirements. One main approach is based on pre calculated pictures, another main approach uses real-time calculation of the picture, e.g. in the headlamp ECU. A pre calculated picture has the advantage that it can be drawn during the development phase of the headlamp and then stored on the control unit. Therefore, the way how this picture is generated can be very complex and in a high detail since this calculation does not have to be performed on the control unit of the headlamp. The disadvantage is that only a finite set of pre calculated scenes are addressable. In effect, this can reduce the flexibility and the dynamics of the system. Another approach is based on calculating the picture in real-time on a control unit. This means that a certain driving situation needs to be interpreted and transformed into a set of parameters which are then used to calculate the corresponding picture. The key challenge is to find a suitable relation between these parameters in order to fulfill all requirements of the light function.

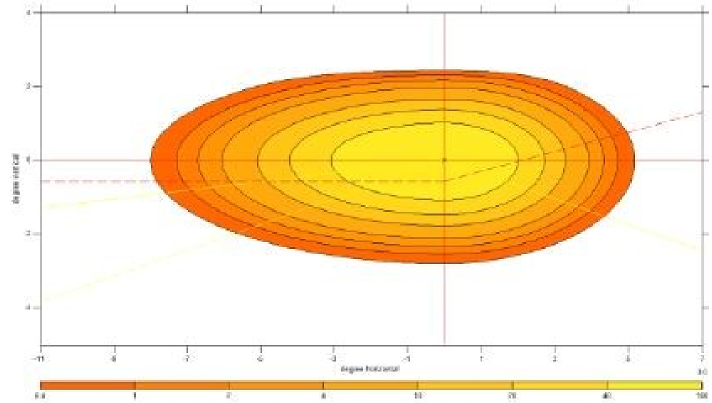


Figure 3.90: High beam with Gaussian profiles

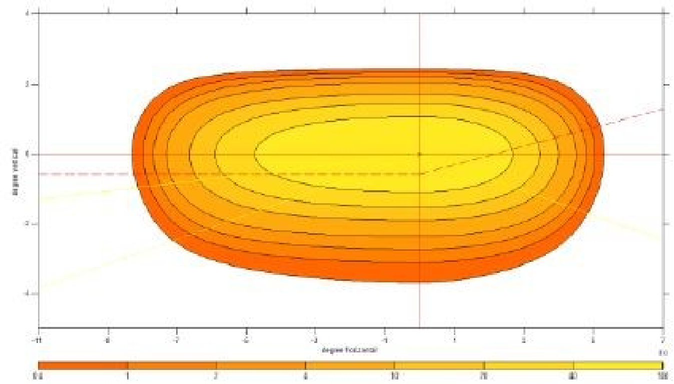


Figure 3.91: Desired high beam with a performance increase of 60% compared to the Gaussian function

Generation of DMD light distribution

One possible description of a light distribution can be made by using a Gaussian profile. The intensities of the light distribution follow the functional dependence in vertical and horizontal direction. By this way, a complete light distribution can be drawn with only a small set of parameters. Beside this advantage, the function also accounts for the logarithmic perception of the human eye with respect to illumination. Therefore, optically appealing light distributions can be drawn as depicted in fig. 3.90 for a high beam pattern. While the Gaussian function possesses many interesting properties, it is obvious that this functional dependence is too simple to actually describe light distributions for a given driving situation. In detail, two important aspects of any light distribution are not covered by this approach: efficiency and flexibility. This can be seen e.g. in fig. 3.91 where a desired high beam pattern is shown. Here, more elaborated functional dependencies are used. When comparing the luminous flux of the desired high beam distribution of fig. 3.91 to the Gaussian profile high beam distribution (fig. 3.90), an increase of more than 60% is obtained.

Furthermore, the high beam in fig. 3.91 still obeys all positive properties of the Gaussian function: The beam pattern is much broader with still very smooth transitions to small illuminances at the border.
Taking such a high beam as a starting point appealing effects can be created already by slight modifications. One example could be a change of lanes. Here, it might be desirable to increase the illuminance on the lane, where the driver wants to drive to, to a similar level on the current driver's lane. In fig. 3.92 the illuminances on the street are shown for the high beam of fig. 3.91 and a slight modification of it. The illumination of the neighbouring lane is significantly increased. Note that the overall appearance of the light distribution is still smooth.

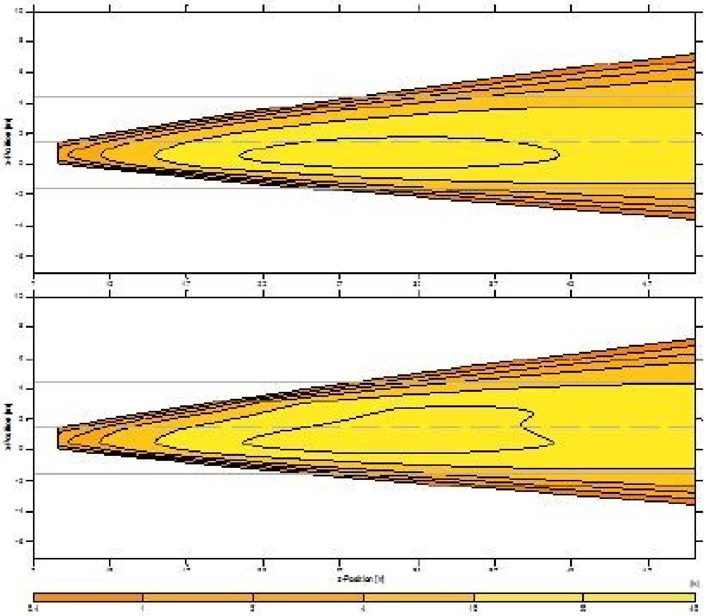


Figure 3.92: Street view of a DMD high beam (single module) fir different situations; "standard" high beam (upper figure) and improved high beam with additional illumination of neighbouring lane(lower figure)

Increasing the details or the dynamics of any light distribution comes with a price: increased computational complexity. No matter which approach is followed – pre calculation or calculation on the headlamp – the current bottleneck is the computational power of the control unit. To actually achieve a real-time rendering of any light function, highly efficient algorithms are implemented which are perfectly adapted to the desired set of features.

Different classes and cut-off line design

In the last paragraphs we discussed how to obtain smooth, flexible and computationally affordable light distributions. In this part, will be briefly described how to achieve light distributions with a cutoff line. While it is in general possible to directly include the cutoff line in the mathematical description of the light distribution, a separate calculation is advisable. In such an approach, the light distribution is considered as an underlying distribution which is then modified by other elements such as the cutoff line. This approach not only allows for a flexible shape of the cut off line, but also gives the possibility to adjust the sharpness of it, even dynamically. This effect can be seen in fig. 3.93, where typical light distributions are shown. While the underlying beam pattern itself is the same for all three pictures, the cutoff line is changed: The upper picture shows a low beam with a very sharp cutoff line. In the middle picture the same cutoff line is used, however, it is made much smoother. This completely changes the appearance of the light distribution. In the lower picture the cutoff line is changed to a typical city light distribution. By using this approach, a smooth transition between these pictures is possible. That means that not only the light distribution can be changed dynamically but also the cutoff line and its shape.

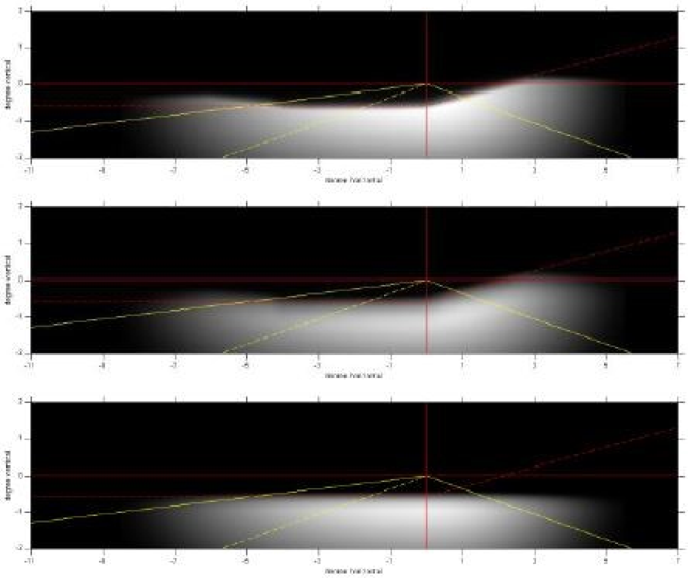


Figure 3.93: Upper picture: DMD low beam pattern with cut-off line. Middle picture: DMD low beam pattern with the same set of parameters as in the upper panel but with e very smooth cut-off line. Lower picture: DMD city light

Applications

Due to its unique optical and electronical properties, the DMD module allows for various new functionalities improving the driving comfort and the driving safety. In the following paragraphs the most important functionalities are described and illustrated, such as an improved adaptive driving beam, improvements of AFS functionality and projections.

Improved Adaptive Driving Beam (ADB)

One of the most important functional improvements with the DMD module is the improvement of the adaptive driving beam. Due to the high resolution, the tunnel can be matched in an optimum way to the driving situation. Therefore, by minimizing the tunnel, the light performance is optimized. In fig. 3.94 the situation is illustrated. In the upper picture the situation is depicted for a series upper class matrix system. The bird perspective shows the light distribution for a preceding traffic in 100 m distance in a height of 1 m above the road. A light tunnel with width of about 6 m is formed. The width is determined by the matrix resolution of 1.2° for the inner segments and the required angular safety distances to the car. In the lower picture the situation is depicted for the same matrix system in combination with the DMD. Due to the high resolution of the DMD, the size of the tunnel is no longer determined by the size of the matrix segments, but can be smoothly adapted to the size of the car (always considering the same angular safety distance to the car). In comparison to the situation without DMD, the size of the tunnel can be reduced to approximately 4,5 m.

So the tunnel width can be reduced to 75% width in comparison to the original situation.

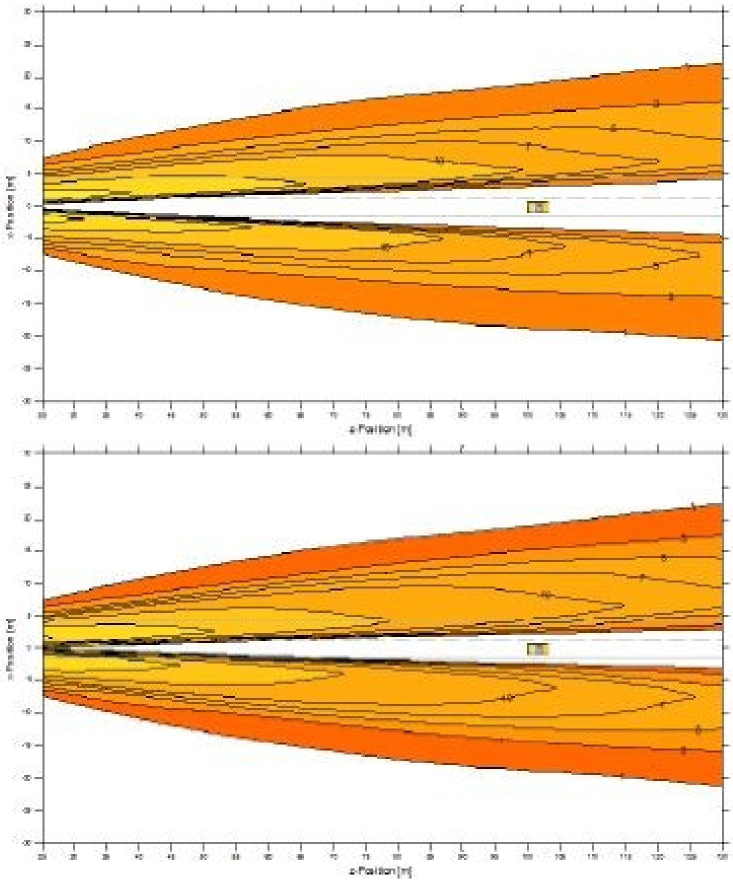


Figure 3.94: ADB situation for a matrix system (upper picture) compared to a matrix system plus DMD (lower picture)

Furthermore, with the high resolution DMD system, the border of any tunnel can be moved continuously. Unlike the system without DMD, the maximal intensity can be put right at the border of the tunnel in a dynamic situation. This enables a much better view than with any other system without support of the DMD.

Improvement of AFS functionality

The intensities can be adjusted such that the light is reduced in areas where too much intensities would lead to a distraction of the driver (such as in the fore field) and increased where a high intensity is desirable (e. g. for increasing the range). In fig. 3.95 the effect of composing a Class C light distribution by an additional DMD (lower figure) in comparison to a classical matrix system and base light (upper figure) is shown: The range of the low beam can be significantly increased on the driver's lane (by about 30%) and at the right edge of the road due to the flexibility of the DMD cut off line shape.

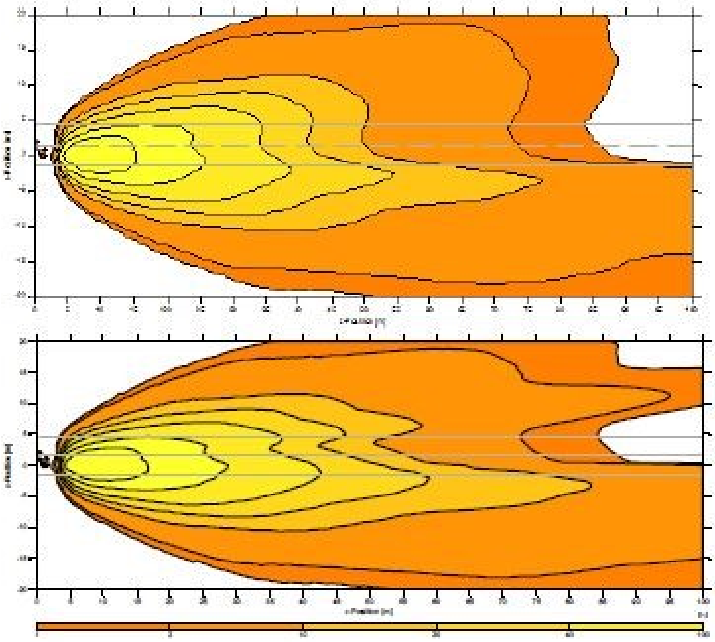


Figure 3.95: Class C in different compositions upper figure: classical matrix system lower figure: additional support from DMD

This flexibility in designing the light distributions may also offer new perspectives for weatherdependent light distributions. Examples are adverse weather light, where glare can be reduced by decreasing the illuminance in the respective regions, or fog light.

Projections on the road

One of the most interesting applications with high resolution headlamps are projections on the road. Due to the high resolution and the good performance of the module, symbols in very good quality and therewith with good perceptibility can be projected on the road. Some categories of projections:

- Driving assistance
- Warning symbols
- Communication
- Animation

The categories driving assistance and warning will be the first step for improved safety. Communication might be a later topic, e.g. for autonomous or automated driving. Animation features, such as coming home scenarios, are not part of this thesis. When designing the projections a potential distraction of other traffic participants has to be taken into account. The design aspects like shape and size, the operating parameters such as projection region (restricted to the driver's lane) and duration of the projection (restricted to some seconds and only during driving) have to be well-balanced. An extensive study which was carried out recently could prove that with well-chosen design and operating parameters no significant distraction of the other traffic participants occurs.

Driving assistance

Projections which serve as driving assistance help the driver to manage demanding situations in a safe manner. Examples for driving assistance can be guidelines similar to that shown in fig. 3.96. These lines might be very helpful in construction zones to help the driver to keep the lane in an optimum way. The positive influence of the guidelines on the driving behavior and on the traffic safety is the result of several experimental studies.

Figure 3.96: Exemplary guidelines

Warning

Warning symbols are used when a somewhat unexpected situation occurs to the driver. These might be symbols in abstract line arrangements such as for lane keeping or distance warning or concrete figurative symbols. For a specific situation, many symbols are thinkable and have been part of various discussions in the recent years. However, when designing a specific symbol, one should always have in mind that it should designed such that it must not be confused with street marking or traffic signs. An example for a symbol is presented in fig. 3.97, where a tachometer as speed limit warning is shown. In a recent study it was proven, that the road projection of a tachometer in case of speeding has significant impact on the driver's reaction: in 80% of all speed limit warnings, the driver reacts with speed reduction. This is about 60% more effective in comparison to displaying the same information by a HUD.

Figure 3.97: Tachometer as exemplary warning symbol

DMD technology as first realized in the Mercedes Maybach S-Class series headlamp offers significant improvements of existing light functions (e.g. ADB or AFS functionality) and the generation of novel lighting functions (e.g. road projections). The resulting gain in driving safety and driving comfort is achieved due to the implementation of DMD technology in high resolution headlamps. The way is paved for a further market penetration of DMD based headlamps.

Chapter 4

Headlamps for autonomous driving vehicles

The introduction and usage of automated vehicles (AV) leads to new challenges and opportunities in the automotive lighting industry. With higher levels of automation, the responsibility of the human driver decreases more and more, meaning that the driver will no longer monitor the surroundings of the car. As a result, intuitive ways of communication, like eye contact between the driver and other road-users will disappear. This can lead to confusion and uncertain traffic situations. New signaling functions have the potential to solve those misunderstandings by showing the intention of the AV. The aim of this last chapter is to make a picture of the actual situation and to project a future on the vihicle to pedestrian interaction.

4.1 Influence a new signal lamp on other road users [16]

The different possibilities of new signal lamps for AV shown by OEMs and suppliers over the past years and the immense number of potential traffic situations generate a long list of scenarios that have to be investigated. To reduce the effort of complex field studies, virtual simulations in the laboratory could be used. The fast improvement of hardware and software in the area of virtual reality headsets, offers a lot of potentials to use this technology for behavioral research in the field of pedestrian simulation in road scenes. In case of application of new signal lamps for AV, this could be a tool to investigate complex traffic scenarios, time, weather and season independent. To validate this as an additional instrument, the behavior of subjects in the virtual environment needs to be analysed and compared to data of similar field studies. The Laboratory of Lighting Technology of the TU Darmstadt has conducted a study consisting of an encounter situation between a standing automated vehicle (AV) and a pedestrian. The tested subjects assume the role of a pedestrian and are set in a road scene by using a virtual reality headset. The AV is equipped with an additional signaling device (two LED-stripes and two displays) in the front of the car. In total six signals are tested in 19 different variations, where different animation times, the combination of signals and different moving behaviors of the vehicle are tested. The intentions of the signals are to show to a subject, when the vehicle will start to accelerate, give a warning before accelerating and show if the road is free to cross. The moving behavior of the subjects is recorded and decision times and crossing speeds are determined. Additionally, questionnaires are used to get a subjective rating of the level of realism of the tested scenario and the usefulness of the different lighting signals. The objective parameters like decision time and crossing speed can be compared to similar real test data to validate virtual reality as a new tool for pedestrian behavior studies in traffic situations. Those parameters are valuable for an objective evaluation of new signal lamps in various scenarios. Using virtual reality headsets for pedestrian simulation isn't something entirely new. A number of studies have been conducted over the past year where subjects are set into the role of a pedestrian at the roadside, getting in contact with vehicles or even AVs. Some studies performed in the past will be briefly described in the following:

1. An gap acceptance study was conducted where subjects were set in a virtual scene on a roadside and were confronted with passing vehicles. The speed of the vehicles was set to 55 km/h with gaps in a range of 25m to 120m. The six subjects were asked to estimate the gap distance and the speed of the vehicles in the first part of this study. The second task was to cross the road between the vehicles while the gap size was varied. In this part, the crossing velocity of the pedestrians was measured. The results of this study are decreasing error rate by speed and distance estimation and increasing crossing velocities for smaller gaps.

2. 15 subjects into a virtual road scene at a zebra crossing. They perceived an encounter situation with an AV, which approaches from 100m with different driving behaviors. The task of the subjects was to cross the road. Additionally to variations of driving behavior, the visibility conditions were changed by using clear daylight, rain and fog at night. The results show that the subjects used speed in clear visible situations and sound in other situations to estimate the driving behavior and make their crossing decisions. Subjects mentioned that an AV needs human driving behavior and no additional signals.

3. An novel communication interface was investigated. To generate a feeling of eye contact, headlamps of virtual car models are replaced with artificial eyes that can focus on pedestrians on the roadside. Subjects were set into an encounter situation with those modified cars and were given the task to make a crossing decision at a zebra crossing by pressing a button. After the explanation of the interface before a test run, the decision time was reduced by 0.3s in encounter situations with the new communication interface.

4. An encounter situation between a shared AV and a pedestrian at a zebra crossing were investigated. The model of the shared AV was additionally equipped with a communication interface with four signals: not stopping, stopping, waiting and start driving. The signals consist of acoustic and visual stimuli. The perceived safety of the 34 subjects, which were introduced to all signals before the tests, increases significantly when the interface is used.

The conducted virtual reality studies are similar in several points: encounter situations between an approaching AV and pedestrian at a zebra crossing. No movement analyzation is done in most of the discussed experiments. Study 1 did the only movement analyzation by calculating the crossing speed . Study 3 calculated decision times for crossing manoeuver by button pressing. In most of the conducted experiments, the subjects felt present in the given scenarios, which is analysed by questionnaires and interviews after the test. The term presence describes a subjective feeling of a subject in a virtual world. It is a sufficient condition for realistic acting in virtual scenarios. Study 4 discussed the term of presence deeply. To get meaningful data about the reaction of subjects in different scenarios objective parameters like moving behavior needs to be analysed. This data has to be validated in a first step.

Research questions

One of the tasks is the validation of virtual reality as a tool for behavioral analyses of pedestrians in traffic situations. This can be achieved by answering the following questions:

1. How do subjects experience the given virtual scenario on a subjective point of view?

2. How does the behavior of pedestrians in virtual scenario correlate with similar scenarios in reality?

3. What is the influence and perception of signaling devices in different scenarios?

The first question will be answered by using questionnaires and interviews after the test. By asking about the role as a pedestrian in the experienced situation and the level of experienced realism of different objects and parameters like the appearance of lighting signals, vehicle movement, environmental elements but also field of view and resolution of the headset, a subjective impression of the level of presence is gained. By recording the position of the subject in the virtual world over time, different parameters like decision time and crossing speed can be determined. Decision time is the time span between the start of a run and the point where the crossing manoeuver starts. The crossing speed is calculated by using the crossing time and the distances needed to cover in order to cross the road. Those two objective parameters are helpful for comparison and correlation analyses with collected data of real tests. Using personal ratings of different signals by the subjects, according to comprehensiveness, increased safety, avoidance of misunderstandings, additional misunderstandings and increase of traffic flow, the influence and perception of the different signals can be retrieved. Furthermore, the decision time and crossing speed offer the possibility to objectively evaluate different signals in various traffic scenarios.

Test schenario

The test scenario is a direct encounter situation between a standing AV and a pedestrian. The situation starts at the point where the AV is standing and the pedestrian is focusing on the AV. In this test, it is not of interest for the subjects how and why the AV came to a standing. It is supposed to be a scenario where a pedestrian is in direct contact with an AV and has to react to it, depending on different signals or moving behaviors of the vehicle. In contrast to the experiments in the related work, no zebra crossing is used. This excludes the case that the subjects can insist on their right of way by crossing the road. They have to make their crossing decisions only based on signals given by the AV. Figure 4.1 shows the top view of the whole situation. The pedestrian is standing on the roadside of a 3m wide one-way road. The AV stands on the left side of the pedestrian at a distance of 3m. In front of the pedestrian is a bus stop, which is reachable by walking over the road.

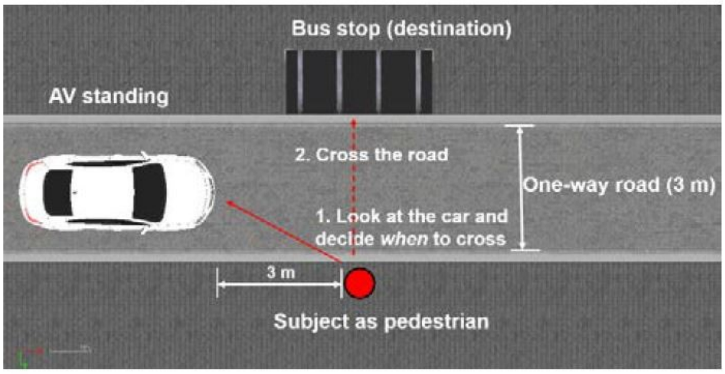


Figure 4.1: Top view of the road scenario with all elements: AV on the left, pedestrian as a red circle, bus stop at the top

In this scenario, the subjects assume the role of a pedestrian. The main task for them in every test run is to walk over the road and reach the bus stop. At the beginning of every run they are asked to look at the AV, decide when or if they want to cross the road in front or behind the AV, and then cross the road.

Laboratory setup

The used hardware in this test is an HTC-Vive virtual reality headset, which has one OLED-Display per eye. Each display has a resolution of 2160 x 1200. The refresh rate of the displays is 90Hz and the field of view is 110°. Additionally, headphones are integrated, which are used to give instructions during the test. The movement area for the subjects is set through the tracking stations of the VR-headset. They are oppositely placed and cover an area of 4.5m x 2m. Furthermore some own photometric measurements of the displays were performed. The measured gamut of the two OLED-displays corresponds to Adobe-RGB. The local contrast was calculated by luminance values of two completely black and white areas next to each other with values of Lblack = 0.29cd/m^2 and Lwhite = 192.62cd/m^2 which leads to a local contrast of Clocal = 664:1. The virtual scene is implemented with the Unreal Engine 4, which is usually used for computer game development and is always up to date on latest rendering techniques. The used vehicle model in the virtual environment equals the model of the real test car of the laboratory of lighting technology, which is useful for later comparison tests in real traffic situations. Other objects like the road, sidewalk and the bus stop have realistic dimensions. The signal elements in the virtual scene are programmed with the Unreal Engine and consist of LED-stripes and Displays. The brightness, color and animation of the signals are freely adjustable.

Signaling and vehicle behavior

Two different virtual signal devices are used in the test: Two LED-Stripes and two displays. Signal positioning: Both elements are attached to the vehicle front (figure 4.2). The attachment of each 40cm long LED-stripe is at the position of the grill in 70 cm height. The two 20cm x 25 cm wide displays are attached under both headlamps in 50cm height. For a better adjustment to the vehicle front, the LED stripes are rotated by ±10° and the displays by ±45°.

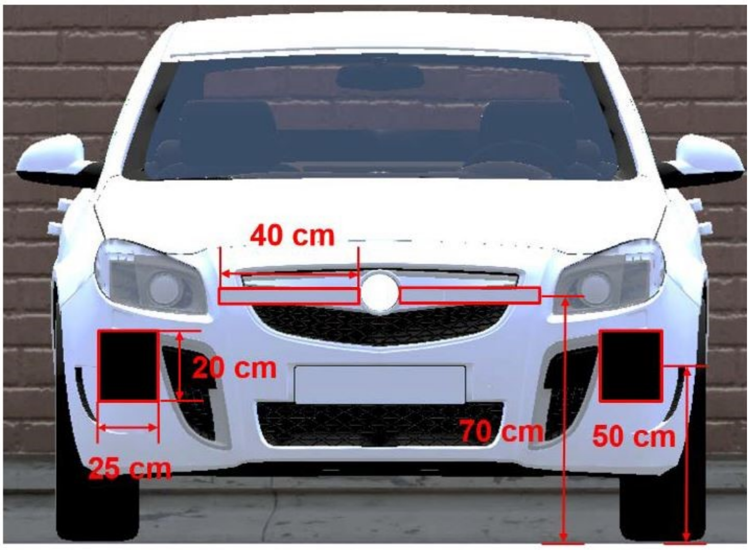


Figure 4.2: Positioning of the two LED-stripes (grill) and the two displays (under headlamps)

Signals: In total six different light signals are used with different variations. They are composed of different moving behaviors of the car, combinations of different signals and different animation times. Figure 4.3 shows all the signals.

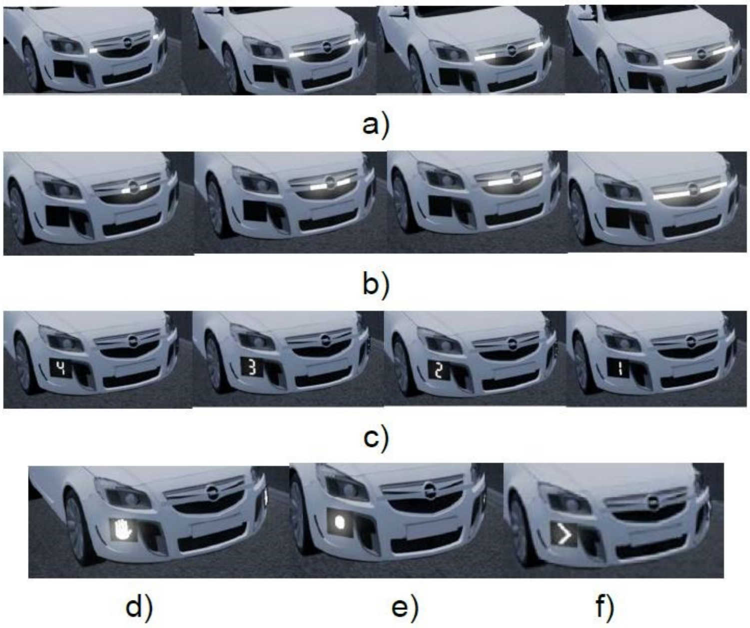


Figure 4.3: All 6 different used light signals: a) chaser outside to inside, b) chaser inside to outside, c) countdown, d) flashing hand, e) flashing circle, f)static arrow

The meaning of signal 1 to 3 is to show to front crossing road users, that the vehicle will start driving after a specific time. Therefore all three signals represent a countdown, displaying when the accelerating process will start. Signal 1 and 2 show this in a more abstract way by using a chaser light animation: The vehicle will start when the two stripes are “loaded”. Signal 3 uses a more specific way with numbers on the two displays. All three signals are varied in time with a 9s, 6 s and 3s countdown. In all 9 variations the vehicle starts driving after the animation with an offset of 0.5s. Signal 4 is a flashing hand on both displays with a flashing frequency of 3Hz. It’s intention is to signalize “ warning, the vehicle will start driving”. The hand will flash for 3s before the vehicle starts to accelerate. Signal 5 is another version of a “warning, the vehicle will start driving” animation. In this case a flashing circle is displayed on both displays, again with 3Hz flashing frequency and 3s duration. Signal 6 is a static arrow symbol pointing in the walking direction of the subject. It’s intention is to show that the vehicle is standing and the road is free to cross. There are two versions of signal 6:

1. Display of arrow for 8s, flashing hand for 3s, accelerating

2. Flashing Hand for 3s, arrow, vehicle remains in standing position

Besides scenarios with signals, there are additional scenarios where no signals are displayed and the vehicle starts driving after different offsets of 3 s, 2 s, 1s, and 0s (vehicle starts driving directly). Another scenario is a direct driving manoeuver combined with a full break after 2.3s. It is varied by showing the arrow symbol on the display after full breaking to signalize the subject, that the road is free for crossing or showing nothing and waiting. All signal variations are listed in table 4.1.

Table 4.1: All signals with their associated intentions and different variations

Signal	**Intention**	**Variation**
Chaser outside to inside	Driving after animation	Duration of animation: 3s/6s/9s
Chaser inside to outside	Driving after animation	Duration of animation: 3s/6s/9s
Countdown	Driving after countdown	Duration of animation: 3s/6s/9s
Flashing hand	Warning AV starts driving	Duration of 3s, flashing with 3Hz
Flashing circle	Warning AV starts driving	Duration of 3s, flashing hand 3Hz
Arrow	AV stands road is free to cross	8s arrow then 3s flashing hand/ Flashing hand for 3s, then arrow
No signal	No intention, start driving after specific time	Duration of standing time: 3s/2s/1s/0s
Driving directly, full break after 2.3s	AV stands road is free to cross	Arrow/ no signal after full break

Vehicle behavior: Figure 4.4 shows the two different speed curves of the AV which are used in the tests. In the full break manoeuver the AV speeds up to 5km/h and performs a full break after 2.3s. In all other scenarios the vehicle accelerates with about 0.66m/s^2 up to 7km/h. This is done after the different offsets between 0s and 9.5 s, depending on the duration of the signal animations.

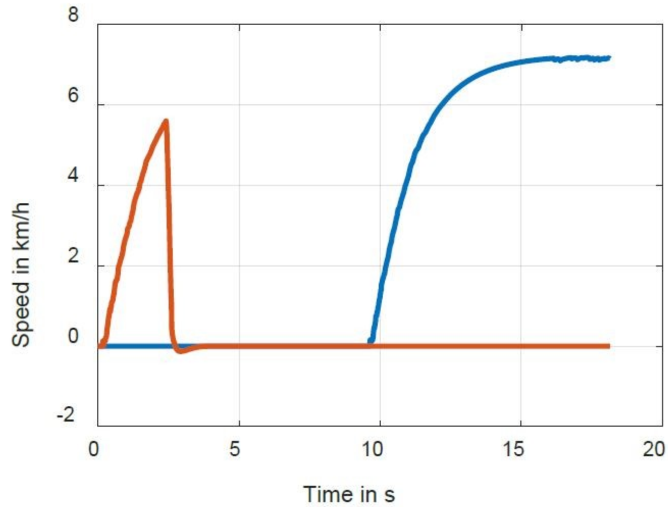


Figure 4.4: Speed curve of the full break maneuver (red diagram) and normal acceleration maneuver (blue digram). The x-position of the normal acceleration maneuver rising graph changes with different animation times

Test procedure

Before the test starts, the subject are asked to fill in a questionnaire with general questions about the experiences in the field of automated vehicles and VR. Additionally to this the simulator sickness questionnaire (which is divided in a questionnaire before and after the test) is filled in. After the subject puts on the headset and gets in starting position of the 4.5m x 2m moving field in the laboratory, the virtual scene is started. The first scene is a neutral starting scene with a marked starting position on the floor (as seen in figure 4.5 a) and b)). The procedure of the whole experiment is explained by a computer voice through the headphones.

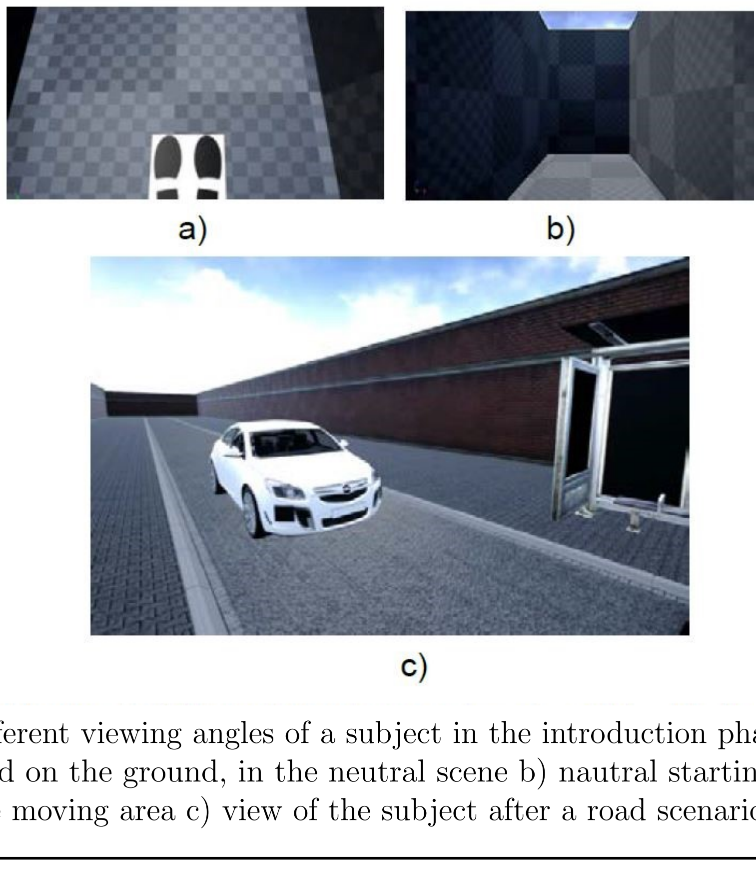


Figure 4.5: Different viewing angles of a subject in the introduction phase. a) starting position marked on the ground, in the neutral scene b) nautral starting position, the walls define the moving area c) view of the subject after a road scenario run is started

After first explanations about the starting position and the movement area, the subject is transferred into the road scene which can be seen in figure 4.5 c). The task about the encounter situation with the AV is explained through the headphones in detail:

- You are on a roadside and your task is to cross the street and reach the bus stop
- On the left you can see an automated vehicle. You can see clearly that no driver is behind the steering wheel
- Imagine that the AV has just stopped on the left side of you
- Be ready that the AV can start at all time
- Look at the car, decide when you want to cross, and cross"
- Don't get in direct contact with AV"
- Now cross the road for the first time, the AV will not start driving now"

After the crossing manoeuver, the subject is transferred back to the neutral scene and is told to move back into the starting position. Before every run the subject receives an acoustic signal to get ready and an optical countdown clock appears on the left side. The subject is asked to focus on the countdown. This guarantees that the gaze is always on the car when a new run is started, therefore the subject can directly decide when to cross the road. The focus of the study is the visual stimulus. To fade out the acoustic stimulus, pink noise will be played through the headphones during the tests. After the introduction phase, the main test is started. For familiarization reasons the first 5 runs are only driving manoeuvers without signals, where the AV starts driving directly, and after 2 s. This conveys the feeling that the AV can start driving at all times. All the 19 different variations of signals and no signals (as seen in table 1) are randomly shown 3 times in 3 different rounds. Together with 5 runs at the beginning a total number of 62 runs is tested which results in a test duration in virtual reality of about 40 to 50 minutes. After the tests, the subject fills in the second part of the simulator sickness questionnaire and a questionnaire about the personal experience in virtual reality with assessments of different parameters and scenes are asked, like:

- Did you feel as a pedestrian in a road situation?
- Did you have the feeling that the vehicle could become dangerous for you, even though you knew that the scene was only animated?
- How often have you experienced the scenario you have just experienced in reality in this way or similar way?

The last part of the questionnaire is about the personal experience of the different signals. After a deep explanation of the used signals and their intentions, the subjects are asked to rate the different signals based on comprehensiveness, increase of safety, avoidance of misunderstandings, additional misunderstandings, increase of traffic flow.

First Results

In total 20 subjects were tested (3 female, 17 male) which were between 20 and 45 years old (mean 26 years). The question "Did you feel as a pedestrian in a road situation?" which was asked after the test is answered on a 5 five-level Likert-scale, where 0 stands for “does not apply at all” and 4 means “fully applies”. Out of 20 subjects, 85% answered the question with 3 or 4 (applies or fully applies). A first set of movement behaviors of one subject at three different scenarios is presented in figure 4.6. The blue solid graph shows the reaction on a 9s countdown. The decision time lies at about 2 s. The yellow dotted line and the red dashed line show the reactions on the full break manoeuvre with symbol (decision time at about 4s) and without symbol (decision time at about 7s).

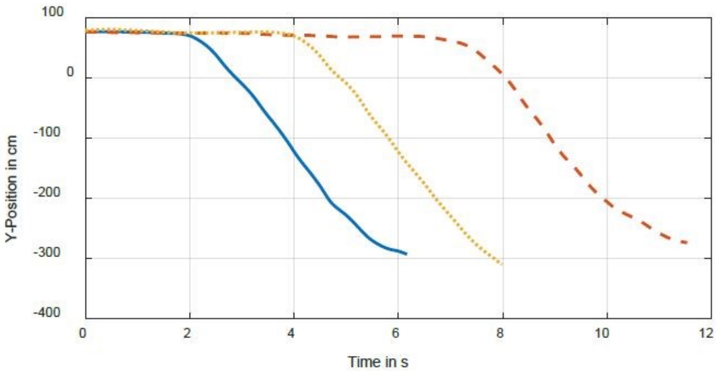


Figure 4.6: Different movement behaviors of one subject at different scenarios. From left to right: crossing at signal countdown 9s, full break and arrow, full break and no signal. The Y-axis in the virtual world runs perpendicular to the road

This test describes a first investigation of an encounter situation between a pedestrian and an automated vehicle by using a virtual reality set up. The personal answers about the experienced level of realism and the feeling of being a pedestrian in a road scenario show a high level of presence of the subjects in the tested scenario. Those are promising hints to realistic acting of the subject in a road scenario. The movement behavior like the decision time and crossing speed as seen in figure 4.6 gives a first hint on the influence of the signals.

4.2 Merging Lighting and Sensing [17]

With the increase of automated driving, vehicles are now equipped with more and more sensors. The benefits and challenges of integrating detection devices such as LiDARS, cameras and radars within the headlamp are now well known and the first serial applications will soon be arriving on the market. What will the next step be? In order to save space and limit other packaging drawbacks, the next step will be to merge lighting devices with some of the sensors. Will common optical systems, light sources, and common electronics be linked to a shared source? This paper compares the different possibilities of lighting-sensing integration. It addresses the main challenges to be taken into account and draws conclusions about possible applications. These integration solutions will bring lighting and ADAS even closer and will help to accelerate the transition toward autonomous vehicles. Within the framework of providing ever more safety on the road and with a view to forthcoming autonomous driving, it is clear that the need for sensing the exterior environment of the vehicle is increasing. Following the introduction of Ultrasonic Park Assist (or UPA), which is already 20 years old, many sensors have been developed and are now integrated around the vehicle. With the increased automation of vehicles, their number will continue to grow, making integration with existing sub systems, such as lamps necessary.

Need for sensors

Along with the increase of end user functions, a growing number of sensors have been installed around the car. One of the drivers for this is road safety, with NCAP organizations all over the world striving to promote systems that will avoid crashes or at least mitigate their consequences. This means that over the next decade nearly all cars will feature some sort of automation, predominantly emergency braking systems. In parallel, totally driverless vehicles will start to appear, e.g. in the form of robotaxis, providing new mobility services on demand. The required sensor sets for a level 1 NCAP system and a driverless robotaxi will obviously differ significantly. However, between these two extremes the opportunity to provide end user value through partial automation is vast, especially for driving in traffic jams or on long monotonous motorway journeys. While the focus on motorways has been predominantly toward the front of the vehicle, maintaining a safe distance, keeping in lane and monitoring the driving path of other road users – new use cases, like automated lane change, demand a similar perception of what is happening behind the car. Automated lane merge extends the scope to the side, closing the cocoon. For the sole purpose of collision avoidance or mitigation, information from a single sensor source may be sufficient. But the higher the level of automation, the more the driver delegates the driving task, requiring heightened perception and situational awareness, leading to dual or triple redundancy. It follows that use cases and the level of automation define the sensor set as well as the basic orientation and mounting positions on the vehicle. For level 3 and higher, the consensus is moving toward the need to include LiDAR sensors in the sensor set. The merging of cameras and radars in particular, which are de facto mandated by NCAP scenarios, generates a significant boost in performance and robustness. LiDAR sensors with varying levels of performance, size and cost will be introduced to support the wide range of architectures up to and including future robotaxi requirements. 360 degree 3D capability in particular will become crucial once there is no driver in the vehicle who can intervene in rare but critical situations, where the ground is not sufficiently even or there are overhead obstacles crossing the vehicle's path. Integrating all these sensors produces challenges. While the main body sections of today's cars remain metal, they are impenetrable by radar waves and therefore the light waves that camera and LiDAR sensors rely on. It is interesting to note that Valeo supplies solutions where ultrasonic sensors are mounted behind metal panels and transmit energy while being completely invisible. Plastic bumper fascias can serve the same purpose for radars, within certain design constraints. All optical sensors, whether active or passive require an orifice or a transparent surface with defined quality, as it becomes part of the optical path. This makes lamps attractive, as they have been initially designed as optical devices. Numerous design constraints, such as temperature, weight and packaging, to name but a few, need to be taken into account. It is therefore important to design the product as an integrated system from the outset. When designing an integrated system, the illumination for the sensors must also be taken into account, especially because LED sources can be modulated, this opens new opportunities for lighting/sensing synergies. Xenon headlamps come with a mandatory cleaning system, providing an attractive proposition for sensors, too. More active cleaning will also emerge, as system availability will depend on a clear field of view and commercial users in particular will demand "permanent" availability. Series production solutions are currently rare, but the car of the future, with its triple redundant sensor cocoons, will host clusters of sensors. The windshield will be one area of application, and vehicle lamps could become another strategic area.

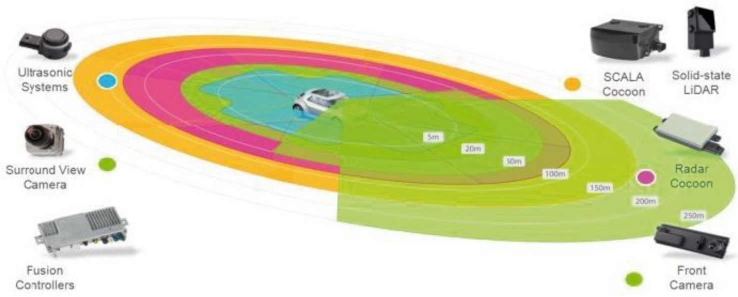


Figure 4.7: Sensors cocoon approach

Cameras

As described in previously, some sensors are suitable for integration within lamps, but this does not apply to all. Long range front cameras used for Glare Free High Beam and for lane and road sign detection, for instance, need to be located on the upper part of the vehicle, which is not compatible with the positioning of the lamps. On the other hand, integration of short range cameras can bring many advantages, especially in corners or in angles where visibility is restricted, as they transfer the ‘driver’s line of sight” to the front of the hood.

Figure 4.8: LiDARs

A LiDAR system, such as Scala, because of its field of view and range, could be suitably placed in a lamp. It could even provide new design opportunities, together with enhanced efficiency if equipped with leveler. Unfortunately, current design trends are making this difficult, due to the compactness constraints. Increasing thermal constraints within lamps are also challenging for this kind of integration.

Figure 4.9: Scala (left) and current integration at the front Audi A8 (right)

The location for this high range LiDAR system is usually central, providing it with an unobstructed view with a range of more than 200 meters. The very broad horizontal field of view of 140 degrees also makes it difficult to integrate it within lamps with highly curved lens found in many vehicles today. Compact LiDAR solutions, such as Flash LiDAR (based on solid state technology) would therefore present less integration constraints. They are used for short range detection, mostly in corners, e.g. for blind spots when manoeuvring a truck. They are very good candidates for integration, with many advantages in terms of design, global architecture and reliability. The loss of performance due to headlamp outer lens transmission can be compensated by the absence of protective glass on the LiDAR. Any thermal constraints, e.g. limited environment around the LiDAR and heat emissions from lighting devices, need to be compensated by providing integration solutions that take into account all aspects of the system. This explains why a complete system approach is necessary at the earliest stage of design when integrating sensors within lamps. Sensing and lighting experts must work together and understand the problems faced by each, both technical and industrial. The integration will also be beneficial for cleaning the LiDAR, which is mandatory for optimum functionality in most driving conditions.

Figure 4.10: Example of Flash LiDAR integrated in headlamp with washing system

Radars

Since radars do not use micrometric wavelengths (visible light / NIR) but rather metric wavelengths, it is reasonable to consider the limited interest of integrating them in lamps. Radars can obviously been integrated behind plastic fenders or bumpers, reducing the need to integrate them in lamps and the corresponding effect on style. The radars on a number of vehicles are already located in place of front fog lamps, offering slick and stylish integration. In addition, as with other sensors, when mounted independently from other exterior components such as lamps, they still need a specific mounting bracket/holder attached to the vehicle, protection against the environment (water, dust, etc.) and a specific connection and harness. Furthermore, they constitute an additional component to be mounted on vehicle assembly line. As for the other types of sensors, the risk of technical interference between the sensor and the lamp is high and a global system approach must be adopted at the outset of the project. Due to the metric wavelengths, the risk in terms of electromagnetic compatibility could be even higher especially on the LED driver which is widely used. A good knowledge of the constraints of the sensors, electronic drivers and lamps is key to solving these potential issues upfront and avoiding design loops and validations which are often budget and time consuming. These constraints should even be taken into account from the early concept phase of generic sensors and generic drivers, if there is the potential possibility of integrating them both within the same lamp.

Merging

As seen in previous paragraph, integrating lighting and sensing in the same unit makes a lot of sense and would solve many issues, but only if the complete system is well managed from the outset of the project, and even during the early concept phase of each of the components. The major issue which is not solved here is packaging. Despite all the efforts to reduce the size of lighting modules (with thin modules where the height of the lens is now 20 mm, without a reduction in performance), the number of sensors in autonomous vehicles has increased, along with a similar increase in the number of lighting functions (High Definition Lighting solutions, using DLP or other technologies).

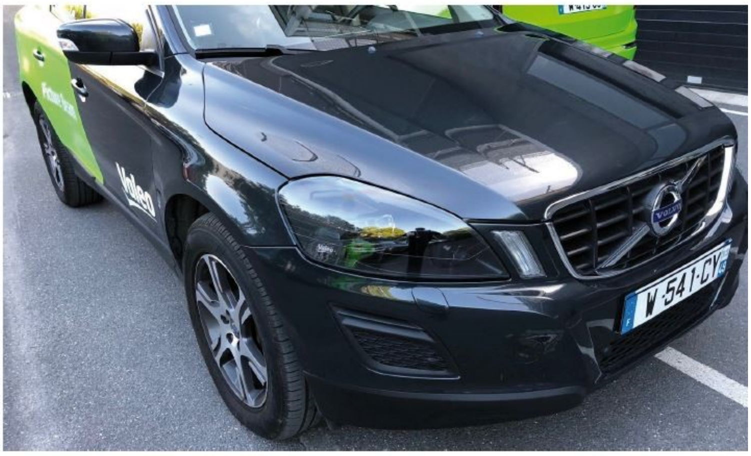


Figure 4.11: Example of a headlamp with integrated thin lens lighting modules and a DMD picture beam

For rear lamps, the packaging issue is similar, taking into consideration both design trends, e.g. very thin application, and the need for new communication via signaling functions.

Figure 4.12: Rear signalling with increased functionality thanks to kinetic technology

It is not realistic to count on more available space on front end, as they have become more and more complex, integrating more safety features, and the new signaling needed for autonomous vehicles.

Figure 4.13: New front with new signalling for autonomous vehicle

All of these considerations point to the need to merge, at least partially, the sensor and lighting functions. Although the possibilities of merging are different depending on the type of sensor, it is possible to split them into 3 different categories:

- “Passive” sensors, typically cameras
- “Active” sensors with metric wavelengths, typically radars
- “Active” sensors, with micrometric wavelengths, typically LiDARs

Cameras

As seen before, this mostly involves short range cameras, used for parking and maneuvering. Integration of cameras within the lamps is feasible if the risks of the different types of interference are taken into account. The next step consists of using the same focalization/projection optical system for the camera part and the lighting unit, then, a beam splitter, e.g. a dichroic mirror to separate the camera sensor and light source (see figure 4.14). If it is not feasible to do this on traditional lighting modules (usually made up of a complex shape reflector, or a combination of elliptical reflector and lens or a collimator type), it is logical on High Definition lighting systems (using DLP, LCD, laser scan, or high density LED matrix). In both cases, a camera and a high definition lighting system, an objective with efficient optical aberration correction is required. This objective will have at least 3 lenses, spherical or aspherical. For a wide field of view and good distortion correction, 5 or 6 lenses may be needed, with a combination of different materials to compensate for chromatic aberration.

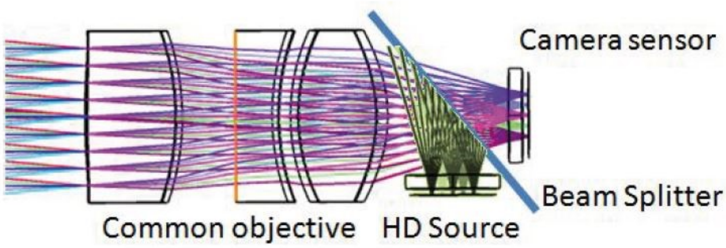


Figure 4.14: Principle of common objective for camera and HD lighting system

Alongside packaging constraints, i.e. the need for enough space for the beam splitter, the main limitation lies in the fact that both FOVs (camera and HD lighting) are strongly linked, with the same ratio as for sensor/source dimensions. However, this could prove to be an advantage if the lighting unit is considered to be dedicated to the camera illumination. It would then allow the camera to work in all external light conditions, with optimized illumination.

Radars

In general both lighting and radar modules can be split into 4 main categories:

- Emitter / Receiver
- Electronics
- Thermal management
- Beam shaping

Emitter / Receiver:Due to wavelength differences, it is obvious that both emitter/receiver and beam shaping must be different, at least for the active optical area of the projection lens of the lighting module.
Electronics: In the current architectures of lighting functions, the ECU, which contains the “brain” of the system, and the separated driver power the LED directly. In more advanced and upcoming systems, such as PictureBeam, an additional, intermediate element will generate the image to be projected. This is the PCM, or Picture Control Module, which converts the information coming from the different sensors of the vehicle and the ECU to a video type signal via a high speed bus, so that the optimized image (including photometric characteristics) can be sent to the High Definition module, using DLP or other similar technology.

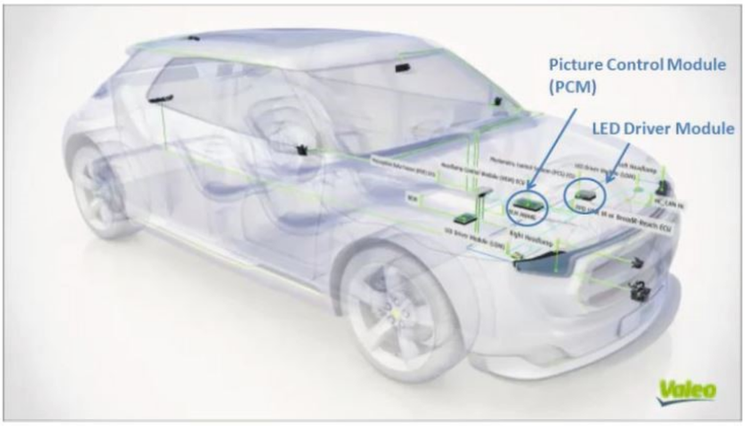


Figure 4.15: Vehicle architecture with picture control module (PCM)

Figure 4.16: Example of a corner radar

Current radars usually have all electronics embedded in their housing. In terms of power supply, radars use voltage regulated solutions, while LEDs are more suited in most of the cases to current regulated solutions to avoid flickering effects. Voltage regulated is also possible with some precautions. However, since radars use much less power than lighting functions, it will be possible to divert some of the power from the lighting driver to the radar driver. Furthermore, energizing the lamps full time to enable the radars to function is not an issue, since the front lighting is permanently on. The main benefit of electronic integration will come from microcontroller centralization within the PCM, which will become the RPCM (Radars and Picture Control Module). As with the PCM, this RPCM can then be centralized with one RPCM only for both headlamps and one RPCM only for both rear lamps.

Thermal management

This obviously, depends to a large extent on integration and design. If the radar is close to the lighting unit, it can be mounted on the LED heat sink and benefit from it. It can also benefit from being embedded on the same levelling system, so that radar performance is increased in many use cases thanks to vehicle pitch correction. More thermal synergy will also occur through the active cooling of the lighting system with a fan. The air flow thus created will help reduce the thermal load on the radar and increase its performance, depending upon implementation, type of fan, heat sink shape and dimensions. Over and above the above-mentioned merging possibilities, it is also possible to install the "radar" part behind the projection lens of a lighting module so that only one module is required, with total continuity of styling. Measurements have shown that initially a thin polycarbonate lens (3 mm) creates a loss between 1dB and 4dB in the radar signal, which is negligible in terms of the global system. Deformations in the signal could occur upon the lens shape at higher angles.

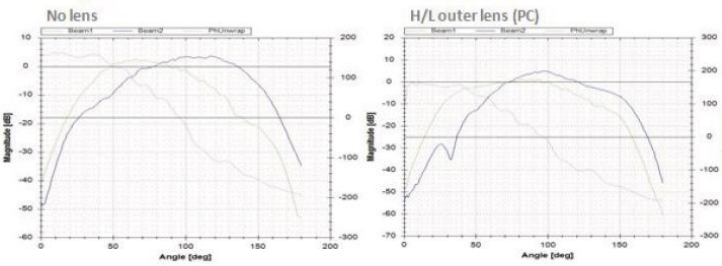


Figure 4.17: Radar measurement without and with headlamp outer lens

With a projection lens of high optical power, e.g. from the Thin Lens range, the impact on the FOV is also very limited, but the losses are higher (up to 15 dB in simulations) if the projection lens is not adapted. This is mostly due to the thickness of the lens, combined with high incidence angles at the top and at the bottom. To avoid this and to make a complete module combining both functions, it is necessary to adapt the global optic combination so that the projection lens has a less negative effect on radar. This must be done at an early stage of the design, with close collaboration between the experts in both technologies.

Figure 4.18: Thin lens module with satellite radar included

A sensor using near infrared light (λ typic $\sim$ 900 nm) is at first sight the most suitable to merge with lighting. Indeed, transparent materials, such as glass, polycarbonate and PMMA have similar optical properties in terms of visible light and NIR. This can be enhanced by reflectors, since there is no constringence effect. Whether we consider a scanning type of LiDAR for long range detection (such as Scala) or a solid state LiDAR with a matrix type approach source and a reduced range, the first merging operation would be to use the same output aperture by combining both the visible and the IR beam with a prism or dichroic mirror.

Figure 4.19: Scala principle

A scanning LiDAR would be then combined with a High Definition Lighting (Picture beam) scanning solution. Beam width is more important with a scanning LiDAR (typically 145° vs. 80° to 100° for a high beam), while vertical spread is lower and does not cover the full low beam / high beam area. Combining source features and primary optics, as well as using complementary visible beams can make this compatible. A solid state LiDAR is an easier use case as it creates segments (from 2° to 5° in width) which are compatible with matrix beam patterns, depending on the targeted FOV for

the LiDAR. As with the scanning system, this “Lighting/LiDAR” module can be easily completed with additional modules to make a complete beam pattern which is safe and comfortable for the driver. The specific shape of each segment must be optimized by defining the primary optic according to the light source. A similar principle can also be applied with a high density matrix of light sources, for both visible and NIR. To take the merging process further means that both the LiDAR and visible light must have the same light source. Initially, high frequency pulsed light is necessary to produce LiDAR pulses of approximately 10 nsec or below. The typical response time of the phosphors used in white LED is 25 nsec, above the previous value and thus making it incompatible. As described before, a solution is provided by using the blue peak of the light source, which is not affected by the phosphor so that it reacts at the required pulse rate. The detector must be sensitive to blue light and synchronized to the source to avoid dazzle from the surrounding environment. An alternative is to use “native” emissions, meaning RGB LED for the white front lighting, but they are currently not at the right level, or red LED for rear LiDARs. Tests have been conducted showing that a 10 nsec pulse of nearly 16 kCd is needed for 30 m detection. With a 100 Hz signal, the average intensity would be 47 cd, above the maximum currently allowed for a tail function. However, it could be anyway applied in a stop function to detect if following vehicles are getting too close or approaching too fast, configuring the vehicle in “pre-crash mode”.
Other integrations: As with radars, other key elements can be combined to optimize both dimensions and costs:

- Thermal management: LiDAR performance is sensitive to temperature and can leverage on the different cooling solutions used for lighting, including heat sinks and fans. With a power consumption below 10 W, their thermal emissions must be taken into account, but they are not high compared to the 50 W to 100 W of high range lighting systems, including HD Lighting solutions.

- Electronics: a common control unit is also a possibility. The Photometric Control System (PCS) is soon to become the LiDAR and Photometric Control System (LPCS), which could also include radar monitoring. The question remains whether to use several small calculators or one large central one. With the same calculator for lighting and LiDAR, a more autonomous lighting function will also be possible, the beam patterns being directly adjusted to the LiDAR data. With the heightened flow of information from the sensors of autonomous vehicles and the new possibilities of HD lighting, a more “local” treatment will have a positive impact on the response time and reduce the network load.

The challenges facing sensor integration are increasing along with the growing number of automated vehicles. A major driver will be NCAP organization, focusing on collision avoidance, where forward-facing sensors will be fitted on nearly all vehicles. Increasing automation levels demand 360 degree coverage and sensor redundancy. This means the angles of the vehicle will play an important role in the positioning of the sensors. As lamps offer integration from a geometrical, electronical and physical point of view, these opportunities will be exploited. These integrations, and in some cases the merging of key elements, will enhance 360° coverage in all driving conditions, including at night and in adverse weather, especially when combined with cleaning systems. This will also promote the introduction of new styling which will remain aerodynamic for energy efficiency and at the same time affordable. Good technical solutions will only be found if the requirements for sensor integration are considered from the outset. This has not always been the case in the past, but Valeo advocates the systematic adoption of this course. The right skills will be crucial to succeed in simulating and designing both a component and a system combining lighting and sensing. A robust design is mandatory for safety systems, and understanding influencing factors and resolving conflicts of interest in a responsible manner is the only way highly automated vehicles can take their place on the road.

4.3 Lighting for automated driving [18]

Automated Driving (AD) will fundamentally change the overall human mobility and usage of cars. The safe and non-disruptive integration of automotive vehicles into "normal" traffic will ask for a new way of communication between the vehicles and their environment. As the existing signal lights, AD signals can play a major role in this communication, in a passive way e.g. as tail light (to be seen) or in an active mode like turn indicators or stop lights. Recent publications show high attention on the automation of vehicles – traffic density as well customer comfort is driving the development towards more autonomy and intense usage of human machine interfaces to increase effectiveness of transportation. Vehicle lighting in this field will take a natural functionality – both to see and to be seen needs to be updated to the future needs of the application. Especially during the decade of a mixed traffic situation, lighting needs to take more communication functionality than before. As 50% of human sensing is based on visual recognition, lighting devices will support the signalization between vehicles as well as with other road users. From a given perspective of road legality according to most common UNECE and FMVSS regulations, the heritage of lighting-based signalization will be shown and indicates the origin of recent legal limitations. Summarizing some possible options for regulation development in the different regions, an outlook based on pragmatic ways forward to implement outlines for color, size, position and intensity of dedicated light signals for automated vehicles will be shown. In order to enhance the regulatory framework in view of further lighting-related communication tasks, justification to both the regulatory bodies as well as to public needs to be given. Further scientific research, organized by the expert groups, can help to formulate a common industry position. The technical boundary conditions such as resolution and necessary LED performance will be discussed. Additionally the regulatory needs will be summarized and a potential way of introduction of such signals will be identified.

Development in traffic in the oncoming decades

Actually the discussion on new lighting for automated vehicles takes a dominant portion in the expert's circles of the automobile lighting scene. There is logics behind: On the one side we do have a traditional set of requirements describing the technical needs of the safety relevant devices, on the other side there are many new ideas which should contribute to road safety as well but not interfere neither mislead traffic participants being acknowledged to the existing ones. The traffic density is increasing, consequently people spend more time in their vehicles, and enjoy more the comfort of automation. In parallel, various functions of the vehicle are now on a technical level where also safety relevant tasks could be taken over. However – this means that such a car might behave different from "normal cars". As long as these vehicles just play a minor role in the running traffic, the given regulations might allow exemptions in particular cases. But as soon as the quantities increase, a transparent picture of accepted functionalities, communication and responsibilities is needed. Soon there will be much more automation on the road. There are some leading cities around the globe on their way to work on fully autonomous people mover concepts in order to improve their infrastructural issues – however, these are just a few hot spots – setting trends but not the majority. Public transport is different from individual transportation which is still the dominant volume. From our market studies we see that the phase of mixed traffic will be the dominant situation in most of the countries for the oncoming two decades.

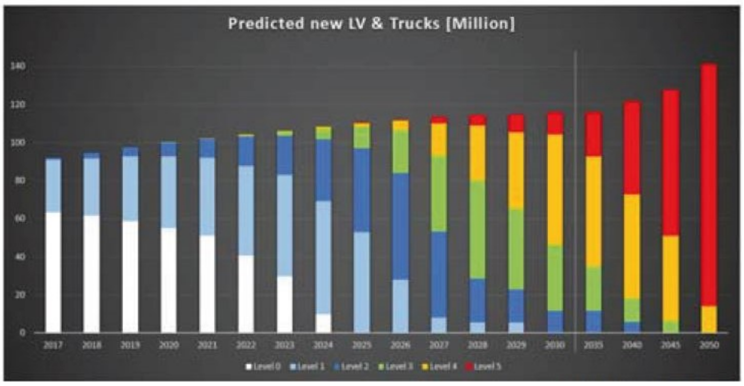


Figure 4.20: Vehicle production outlook

When taking this development of mixed traffic into account, there are new aspects of safety to be taken into account. Automated vehicles might behave different - First, it needs to be seen that automated driving cars might behave different from a driver driven car. More Information through more sensors will be available, a higher speed of calculation / reaction possible, the “Car-brains” can be programmed different from human (false) behavior or intuitive self-protecting reactions. Self learning software (AI) based upon autonomous driving results and incidents can be implemented, resulting in different behaviour. Else, vehicles may be connected to other vehicles - but may not connect to humans outside the AD vehicle. Traffic will develop further, and as a consequence it will increase. Automated driving systems will help to balance better for the comfort of the drivers as well as for safety and limiting the safety risks induced by the density increase.

Do ADS equipped vehicles need a signalization at all?

In expert circles, discussions are ongoing s some of the manufacturers are of the opinion that the machine operates even more trustful than a human body – however, there is an interconnection to the question of responsibilities. In this question, as long as the AD indicator is off, the driver is responsible. Whatever car function is activated. However, some national authorities have created facts: In US, NHTSA has made a statement that ADS operated vehicles need to be differentiable from normal vehicles. Also in Germany , the so called Ethics commission has mentioned the necessity of information to other road users in Art- 5 and 16. This more fundamental discussion has been held already in 2015 and 2016, and does not intrinsically mean that ADS signalization must be done with a light signal. There is no decision taken on technologies, and indeed, light is only one option amongst lots of others – radio signal as well as IR, WiFi or others. But on the other hand, WHY NOT light?

- 50% of the human recognition is performed via visual (eye) input
- 80 % of the outer brain skin is dedicated to operate visual signals

- >99%of the countries of the world, road users are familiar with light signals - Especially the fundamental things: Red means stop.

There will be an international rule or regulation - Recently there is no complete exchangeability of regulations for safety relevant parts of vehicles. Although UNECE prescribes for most of the countries, there is one country which has its own system – the USA. From a global perspective, this needs to be taken as a key point – A global approach, eventually via a Global Technical Regulation (GTR) could solve this. Especially the ADS light device can trigger a new option for convergence: Both UNECE and US' SAE organizations are actually working on draft technical spec's – and the content can be synchronized. This can set the pace for future international lighting reg's and standards. Lighting can play a key role in the risk reduction.

The timeline for these regulative topics

From the US side the work in SAE task force J3134 is leading – the technical recommendations can be set End of 2018 so that US authorities can make use of it in 2019. In the UNECE framework, the discussion will be aligned with the numerous panels dealing with the even more fundamental questions on automation and autonomous vehicles, such as truck platooning or infrastructural needs, in this context, the lighting experts have indicated their readiness to work out draft proposals as soon as UNECE likes to review.

Ways forward to implement a signal for automated mode

Today there is already signalization on the car. As a consequence, the question to be answered first is: What else do we have to signalize to improve safety? In the experts panels this question has led to a multistep approach:

- First, the safety aspect of the indication of automated operation to be ensured – the vehicle gives information to the surrounding that it is in automated mode and therefore might behave different from a driver-driven vehicle. The simple message: "On" which will be immediately understood as "I'm in Automated mode" will help, the simpler the better. This so-called MARKER LIGHT can take the very basic functionality with dedicated signalization color, easily distinguishable from any other signalization, bright enough to be detectable next to other light functions and so setting the framework and boundary conditions for the light signal outline.

- Beyond this, communication between the vehicle and its surrounding can support safety. However this communication is a complex topic- we need to cover the capabilities of different countries, environment and social factors. Although also here we could say "the simpler the better", various idea's pop up and need to be investigated. For the communication, scientific studies will be carried out to find a new common language to further improve traffic safety. After a short phase of intellectual silence, the human sense taught the experts the straight forward logics of traffic safety which is obviously also the strength of the UNECE road traffic convention. The easier a signal is detectable, the better it is for the use in traffic. Therefore, the discussions on AD SIGNALIZATION will take a longer period of discussion. The communication e.g. if vehicle intentions might be supportive to enhance traffic safety at first glance, but taking international rules, cultural differences and infrastructure into account, the picture changes. A light signalization beyond the simple AD on/off needs to be easy to understand at day and night, and public should easily get used to it. Road users are acquainted to light signals, this is a good platform. Therefore it needs to be independent from any

- infrastructure and traffic mix in any country
- from national traffic rules
- from vehicle classes (passengers, trucks, busses), and above threshold independent from the level of automation

And seeing the relevance of traffic safety globally, especially for children but also for tourists and foreigners, the intuitive perception is a must. Therefore the second step to work on communication with a SIGNAL LAMP will be done after having prescribed the photometrical outline with the MARKER LAMP. This framework will put the signalization for automated vehicles into the given context and consequently pave the way towards communication.

Technical requirements for a light technical signal

From the visual knowledge, most of the recent options for the outline of a light signal can be condensed to a list of parameters to require minimum visibility related to safety. The four sections of parameters are the geometrical visibility and size, position, color and brightness.

- **Geometrical visibility and Size**
  The automated vehicle is intended to react independently from any human control – therefore the visualization of this mode. Needs to be recognized from other traffic participants. This incorporates all road users like pedestrians, cyclists, two-wheelers, cars, trucks and lorries. Compared to the visual requirements for the driver of a truck having his eyes on more than 2.5m height above the road surface and a 10 Year old school kid having the eyes on approximately 1m, the height is one of the influencing parameters. But also the perspective where the observer might be located will strongly influence the view angle of the signal. Else, dependent on the speed, the variation of the view angle indicates that a description needs to be related to the needs of a potential observer. This potential observer application can occur in the full operation space around the AD vehicle. As a consequence, In the case of an AD-marker lamp device which may also be comprised of more than one separate unit, the geometrical arrangement(s) as installed at the vehicle seems to be acceptable, if the partial light distribution of each single separate unit is overlapping with each adjacent partial light distribution inside a horizontal angular range of 360° and in a vertical angular range as specified for the relevant category in a geometrical position corresponding to a distance of 20 m, from the vehicle on a vertical plane that is perpendicular to the longitudinal axis of the vehicle. The Vertical visibility will not need to achieve full omni radial perception and therefore can be limited to 5°D to 30°U if $h < 100$ cm , 15°D to 15°U if 100 cm $\leq h \leq$ 180 cm and 30°D to 5°U if $h > 180$ cm. This does not intend to describe a rotating beacon on the top of the car – the idea is to prescribe the real observer needs from an application perspective. Indeed, an overhead mounded device might reach these requirements, but the body and frames of existing vehicles do allow much smarter solutions and there is a huge difference in the light technical

settings of a sports car having maximum height of 110cm versus a lorry with about 350cm height. A requirement on size appears to be partly redundant visual recognition must be given, therefore a minimum requirement of min. size: $25cm^2$. The maximum size definition does not make sense at all, therefore the outline of the body construction of the vehicle can be the guiding dimension. From visual appearance, a huge display in the grill of a passenger car can meet these requirements as well as a small integrated reflector device in the bottom area of the windscreen of a light truck or a lorry.

- **Position**
  Taking the above mentioned into account, especially the front end of the vehicle requires special attention. There should be freedom to integrate into different body shapes – also here the recognize ability needs to be confirmed by application test and their requirements. Dependent on the position, the AD signal can be seen easily on the front grill of the flat sports car, but hardly visible behind its screen as the inclination of the glass will result in phantom light effects which make it impossible to see whether the light is on or not. The inclination and their consequential optical influence on recognition needs to be taken into account. Describing the minimum requirements on visibility can help here as well: as long as the device is mounted in a way that observers can properly recognize, no restriction should be given. As the vehicle needs to fulfill minimum mounting heights of light technical devices on the car of >250mm also for other devices such as DRL or Turn indicator, this appears to be logical for an AD signal as well.

- **Color**
  At first glance, color appears to be a rather simple and easy subject to be agreed on. Taking into account that colored signals are also used in various traffic safety related areas like signs and surrounding, it becomes clear that the decision to introduce another color might not be easy. The color will play a major role as the key identifier for the AD signal –as intensities of other functions will be in the same order of magnitude, the option of an individual blue green color will allow to differentiate. Recently there is the discussion amongst experts ongoing whether a white signal is sufficient and prevents from confusion versus the approach to define blue green as the AV color – scientific studies at Universities are now carried out to guide the regulators. UNECE prescribes in the “Road safety convention” (WP1 UNECE) the general outline of traffic signals. The general outline of signalization is given: to make sure any traffic participant can understand, the very basic conditions are given – such as: at the front of the vehicle, lights need to be white, at the back they need to be red. Subsequently, no red lights at the front allowed. Also the white lights at the back are a special case, only illuminated when the vehicle is backing up. Furthermore, in CIE a broad study has been published – in the document “CIE S 004/E-2001 “Colors of Light Signals” and CIE 107-1994 “REVIEW OF THE OFFICIAL RECOMMENDATIONS OF THE CIE FOR THE COLOURS OF SIGNAL LIGHTS” the typical usage of signalization colors in safety use are described. To conclude the findings of CIE, there are some recommendations applicable for the use on AD signalization. Independent from any color, the study shows evidence that the more saturated the color is, the better signalization effect is. Else, this study gives an overview of the colors already in use with defined color space, and the freedom of use. Purple is not a suitable color for light signals since it is often

confused with red especially since the atmosphere selectively absorbs the blue component of purple. Moreover, the chromatic aberration and/or refractive error of the eye will often cause a purple signal to be seen as a red signal with a blue halo or as a blue signal with a red halo. Violet is not a suitable color for light signals as it is often confused with blue, has a limited visibility range and may be seen as blue with red haloes or red with blue haloes as for purple. Orange is not a suitable color for light signals because it is often confused with red and yellow. Obviously also magenta and pink have a high chance to be confused with red. The yellow-green colors may be confused with yellow or red by persons with defective color vision. Color vision defective observers are likely to confuse white and green. Blue is not a suitable color for long distance visual signals because the eye is relatively insensitive to blue light , else blue and green are confused by normal observers for signals that have small angular subtense or a low illuminance - At low illuminances and for signals of small angular subtense, the normal visual system tends toward tritanopia (blue blindness) so that blue may be confused with green, white and yellow. From the analysis of the scientific investigations from CIE, it appears logical to go for a BLUEGREEN (Cyan) signal color , for the case that a different color than white is wished.

- **Brightness**
  In this section, the photometric requirements are described. Visually the AD signal – especially at the front of the vehicle – needs to be distinguished from various other signals such as turn indicator, stop lights and daytime running lights. Therefore the values should represent comparable data. In the different panels, the maximum value at daytime is discussed in a range of 260cd to 300cd and a minimum value of 50cd which is coherent to the DRL values – a compromise appears to be feasible. Different from the DRL functionality which is fully adapted to visual recognition at daytime, the AD signal needs to operate at night as well. Then, daytime values would be far too high – therefore, a second range with values of at night, 2.5 cd min. could be acceptable. Else especially in twilight time (when ambient light outside is between 1,000 and 7,000 lm). Therefore the max. value of 140 cd max. (the same max. value for Front position) is under discussion. AD marker/signal consequently should be mounted in a proper visible way, as big as possible and as small as acceptable in blue green color at high intensity to be distinguishable from any other function.

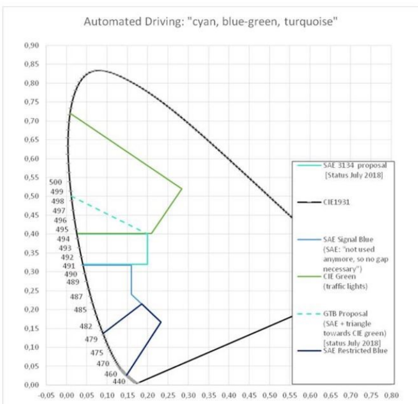


Figure 4.21: CIE 1931 colour diagram with focus on bluegreen

To justify , the 6 SDCM value for a blue green color shows majority of observers will distinguish from signal green as well as signal blue. Else, the high saturation for signal function will increase visibility, and green light today is used only in “non moving” traffic lights. So, a potential overlap with green for (moving) vehicles will not affect safety.

Technical solutions for the light generation

The individual view to each parameter of this lighting device appears as a technically achievable goal. But the combination of these light technical requirements leads to an increased threshold for especially the technical layout of the light source. Reaching more than 200cd intensity is not rocket science – but doing this in a very limited color field with as less energy as possible, it develops to a challenge. The first option to realize such a signal device will be the use of a colored filter glass in combination with a white light source. Colored filters are a fair way to meet the needs of the signalization color, capable to withstand temperature as well as other endurance and environmental requirements. However – the transparency of such filters is the lower they come closer to a narrow bandwidth. As a consequence, the white light source behind the filter needs more light which leads to a higher energy consumption. The system efficiency of such a device will have clear limitations. Using LED technology will allow to realize the combination of additive colors with high-efficient light generation. Three different options for LED can be differentiated:

- An additive mixing RGB LED matrix
- A phosphor converting LED source
- A discrete emitting LED source

Bluegreen via additive mixing RGB LED matrix

For the RGB matrix the basic idea is the classic additive color mixing system: Have a discrete (almost) monochromatic light source in RE, GREEN and BLUE next to each other, with minimum spatial room in between and identical polar luminous intensity distribution, white light will be detectable as mixture from this. All colors can be tuned by variation of the three individual sources. This appears to be a close-to-perfect-solution – with a microcontroller programmable and added to a display, any color at any intensity could be maintained. So far the theory – limitations of the system come from the compromises the engineers have to balance: To reach minimum special distance for an acceptable visual color mix impression, the dimension of the individual LED chip needs to be small – thus the maximum output limited. Also, the level of monochromatism of the individual LED chip is leading to a limitation of the saturation of the mixed color. For the approach to combine visual signalization with communication as well, this technology will be an important subject especially for the display discussion.

Bluegreen via phosphor converting LED source

The adaption of the emitted energy of the P-N semiconductor from high energetic visual and nonvisual spectrum into a narrow band emission by applying a phosphor layer on the entire LED chip appears as an efficient way to combine energy efficient light generation with narrow band color.

Bluegreen via discrete emitting LED source

Construction wise, each LED is a stack of multiple semiconductor layers with different composition and doping concentration. The semiconductors used in LEDs differ from those in integrated circuits both in terms of chemistry (LEDs compounds like GaAs and GaN instead of Si) and the manufacturing process. The layers of an LED are deposited using a technology called organometallic vapor-phase epitaxy, which has clear advantages over competing techniques when considering factors such as the control of growth rates, uniformity and throughput. The term "epitaxy" comes from the Greek epi (upon) and taxis (arrangement), and explains well the growth on a substrate uniquely determining the orientation of the grown material. Epitaxy ensures that all locations on the wafer have the same atomic orientation and prevents from defects in the structure that reduce efficiency. The various competing physical and chemical processes result in a highly complex system, and growing any given layer of an LED with uniformity and reproducibility requires simultaneous optimization of a large number of input parameters (pressure, temperature, multiple gas flow magnitudes and ratios). The optimum growth conditions for each layer must be developed individually, and the LED performance has a high sensitivity to not only the thickness, composition, doping (including residual impurities), and quality of interfaces for each specific layer, but equally to the specific attributes and process conditions used for growing both the preceding and subsequent epi layers in the structure. The combination of the right materials already in the epitaxy of the LED wafer will allow a close-tomonochromatic cyan radiator with maximum efficiency, compared to a phosphor conversion, this method will allow a gain in achievable lumens per Watt. There are different technologies available – a technology neutral regulation, performance based, will allow the best compromise between the efforts spent on the technology side versus the most energy efficient solution.

Display technologies

The signalization of automated vehicles required basic needs on photometry in line with given safety requirements of lighting installations already existing on the vehicles. However, opening this subject to the future projection of enhanced safety, communication comes to the plan. Whilst the signalization creates this light technical framework, communication can leverage on it and add further information which helps to inform the road users about special means. The communication in traffic needs to comply with fundamental requirements – although in the Industrial world reading and writing is always taken as a given, for traffic safety the situation is fundamentally different. Safe interpretation of the signal as well as the speed of recognition are the key carriers of road safety. Taking into account that a signal for automated vehicles will be used globally, the different cultural influences not just in regions but also in infrastructural perspective need to be taken into account. As a consequence, this will generically lead to further forms of communication – here, symbols and pictograms offer more opportunities to harmonized solutions than alphanumerical, but the first generic investigations indicate that there is still some room for further development. A corporate approach to let lighting experts work with communication experts can be favorable and is brought to the panels as suggestion. Beyond the straight forward indication of the activated mode by using a marker lamp, the communication of intentions and/or information will require a device with a minimum capability of controllable pixels. The usage of at least monochromatic devices with resolutions in the order of 100x300dots appears as practical. For the first investigations and bottom up experiments, displays in different LED configurations are in use. From a technological perspective, the achievement of the light intensities being needed to realize a signaling function such as a front turn indicator with the same device as a symbol display in acceptable resolution is challenging. However, dependent on the basic needs of traffic safety, the size and locus of the device may follow the outline of the described ADS marker – and signal lamp, and prescriptions on content, symbolism, contrast and logics need to follow the next step of definition in regulation. A new vocabulary and semantics needs to be defined. The introduction of further automation in road transportation will lead to an increased demand for reliable communication between road users. Here, road safety improvement can be provided by the introduction of a dedicated ADS signal. An additional ADS marker lamp can be used to indicate the status, further ADS signals to communicate with other road users. Traffic density will increase hence road traffic risk, and automated driving in itself does not decrease road traffic risk due to increase traffic density especially because of non-car users and the new effects of mixed traffic. Lighting (as 80% of human sensing is based on visual) for AD signalization however could help reduce traffic risk in increased density context. A new lighting regulation will be achievable on global level, including design rules in geometry, size, position, color and brightness, and light source technology options are at start. To achieve this, LED technology paves the way for improved road safety by enabling broad use of bright, energy-efficient and car life light sources for all lighting applications, offering huge opportunities in signaling to fulfill future demands for autonomous driving and electrical vehicles. In a first step, standardized LED light sources can build the platform for mass adoption, the serviceability of these light sources create the opportunity to use latest technology to maximize system performance towards increased safety. This will create a way forward to make use of broader displays as well. Implementing display technologies into the lighting concept of a vehicle will allow to improve traffic safety by communication. The oncoming decade will be the time to materialize this.

Conclusions

Implementation of the matrix technology largely will bring for sure an increase of safety and reduction of accidents. The near future will be about interaction between vehicle and pedestrian and this technology will play a key role. Transition from matrix to high resolution headlamp is the natural evolution and in the future will not be available to only premium vehicles but will be present to all vehicles as is today the infotainement and navigation systems. We must consider what is the actual transition of the headlamp market. The majority of market presence is still halogen solution but the transformation is taking place. It wasn't possible for the HID headlamps to be used on the non premium vehicles but is being demonstrated that the LED lighting will be the future for the majority of the vehicles. Low cost LED solutions are being developed showing an increasing performance with a slight cost increment with respect of the halogen but this is only the beginning. In the next five years LED headlamps will cost as the halogen ones and the implementation will increase drastically. Than the transition to the matrix technology will started to extend more and more. Let's consider another big factor of influence, the autonomous driving. As it was discussed in the last chapter interaction between vehicle and pedestrian will be a new demand. Autonomous driving will revolutionize our mobility. The pedestrian must interact with the vehicle since will not be possible to interact with the driver, it's strange but with autonomous driving the concept of driver changes and we can consider only passengers. So new lighting signal are necessary in order to operate in safety conditions. Electric cars demand high efficiency energy in all vehicle systems. LED lighting increase the electronics but optimize energy consumption allowing a customization of the lighting in function of the situation. We are in the begging of big a transition period of mobility. Electric vehicles, autonomous driving and pollution reduction are the main drivers towards change of our mobility model. We must admit it, our mobility model is old, this because the environmental impact is too big and now that climatic change is not an idea but a reality, what is the right path to follow in the future? Neglect it and not thinking about it or change and put our knowledge to work.

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