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Automobile headlights:
Common problems and possible solutions.

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Abstract:

This thesis examines the most common problems (such as glare and poor performance) of automobile headlights and provides theoretical solutions. The common problems are delineated by explaining and analysing the headlight's elements such as light sources, optics, and the international laws they need to follow. These problems are then analysed more in depth, based on existing research and an online glare survey conducted by the author. Before coming up with solutions some of the existing state of the art technologies are described and then analysed, in order to garner inspiration for the final solutions and to evaluate their feasibility. By exploring how glare is treated in other industries, we can gather important evidence that could be applied to the automobile industry. Finally, a set of theoretical solutions is provided to eliminate the aforementioned issues, potentially providing glare-free and high quality and high-performance headlamp lighting in a real-life situation.

Automobile Headlights:
Common Problems and Possible Solutions

Radu Rusu 2023

Acknowledgments

I would like to thank my supervisor Henrik Clausen for providing support, giving feedback and advice throughout the semester.

Furthermore, I would like to thank all the lecturers and professors that have taught me valuable knowledge for all these years of my Master's.

Finally, I would like to thank my family and girlfriend, who supported me during the process of writing my thesis.

Table of Contents

1. INTRODUCTION

1.1 Preface

Automobile headlights are an indispensable safety feature of vehicles: they provide adequate lighting for drivers to navigate roads during low-light (and/or low-visibility) conditions and they enable other drivers to spot other vehicles at a distance. Vehicle headlamps also come in many different designs, in order to fit with the overall aesthetics of a car and can have different light sources, optics and various principles of operation.

Regardless of the type of headlight, this technology is prone to issues, such as glare or inadequate levels of lighting, that can compromise their performance and lead to unsafe driving conditions. Headlight problems can be caused by many factors: inadequate design (as noted by the Insurance Institute for Highway Safety), misalignment, dirt, and age. It is critical to have a good overview and understanding of these factors in order to achieve solutions that can either eliminate or minimise the impact of the most common headlight problems. Various solutions to the most common issues already exist, however, they are not very widespread yet and many drivers still struggle with headlight-related problems.

By reviewing existing literature and conducting a survey about glare perception, this research paper aims to analyse the most common problems associated with automobile headlights, their causes, possible solutions based on the state-of-the-art technologies, and subsequently delineate a theoretical design solution that can mitigate the most widespread problems.

1.2 Motivation and Vision

There is a lack of active research about lighting in the automobile industry, most manufacturers appear to concentrate more on criteria such aesthetics and meeting law demands, rather than the perception of automobile headlights, both in the cases of pedestrians and drivers. However, it is important to note that the lack of easily accessible research could simply be a symptom of the highly competitive and therefore secretive nature of the automobile industry.

In a RAC study of 2700 participants in the UK showed that most drivers (89%) believe some or most car headlights on UK roads are too bright, with a majority of them (88%) stating that they get dazzled by them while driving (*Blinded by the lights – nearly one-in-four drivers think most car headlights are too bright*, 2022).
In a similar study, conducted in the Czech Republic, with 539 participants, the majority of respondents experienced glare at least once a week and some almost daily (Viktorová, Mičková and Stanke, 2022). Finally, two studies conducted in Iran showed that disability glare is a significant issue, especially when using high beams and, additionally, depending on the age of the driver (Mehri *et al.*, 2017, 2021).

A law requiring the use of automatic headlights, that turns the low beam on or off depending on the surrounding light levels, was passed in Europe in 2019 ('Regulation No 48 of the Economic Commission for Europe of the United Nations (UNECE)', 2019), which is a step towards progress, but it still is a very basic demand and it does not take in consideration many of the complexities and challenges of headlight technologies. In addition to this, only in 2022 (effective 2023) a law was passed in the USA in order to allow cars to have adaptive beam technologies, which amends some old and outdated requirements in order to allow manufacturers to legally use more advanced types of lighting technologies in automobiles. (*NHTSA to Allow Adaptive Driving Beam Headlights on New Vehicles, Improving Safety for Drivers, Pedestrians, and Cyclists | NHTSA*, 2022)

Many problems such as too low light output that doesn't enable the driver to see the road properly, or the opposite, too high output and/or bad alignment causing excessive glare have been existing since the 1920s (*The New York Times*, 1926), and many issues haven't been completely solved since. The lack of widespread advanced lighting technologies in the automobile industry could be due to various reasons such as inadequate technologies, outdated and/or superficial laws, lack of public awareness.

Therefore, the author of this paper plans to complement existing research about this particular topic and find possible theoretical solutions that could pave the road for better automobile lighting and inspire future works.

Based on the initial research for this topic, the following initial vision has been formulated:

"Imagine if we could have vehicle headlights that could illuminate dark roads very far away, without creating glare for other road users."

Which led to the following research question:

"How can car headlights provide good lighting with a very long beam range without causing discomfort and disability glare for other road users, and how can these seemingly antithetical attributes function together?"

2. METHODS

This research paper aims to identify the common problems with automobile headlights and suggest possible solutions for those issues. The study is conducted through reviews of relevant literature, analyses of relevant state of the art automobile lighting technologies, and an online public survey about one of the most common headlight problems, which is glare.

The research will use both qualitative and quantitative data. After explaining headlight theory and delineating the most common problems, such as glare, an online survey about the most widespread issue will be conducted in order to have an understanding about the public opinion of that particular problem that car headlight may have. State of the art principles of automobile lighting technologies and studies will be analysed and used as a starting point for the final design principles that will aim to solve the most widespread issues with automobile headlights.

3. THEORY

In this section the basic working principles of car headlights will be explained, together with important notions and keywords, in order to create a theoretical basis for the paper and also enable the reader to understand in a clear manner the rest of the paper. Some examples of headlights will be shown, but it is important to note that they come in many different types, shapes, principles of working, therefore only the theoretical principles of functioning will be explained. While car headlamps may contain different types of lights, such as low-beam, high-beam, fog-lights, direction lights and other types of auxiliary lights, only the first two will be considered for the purpose of this paper.

Low-beam headlights, also known as dipped-beam or passing-beam, provide adequate forward and lateral illumination and are used during low light situations. The United Nations Economic Commission for Europe (UN ECE) regulations specify the beam of light that low-beam headlamps produce as sharp with an asymmetric cut-off: the beam is separated in half, with the half closest to oncoming drivers being flat and low, in order to prevent glare for oncoming drivers, while the half closest to the outside of the road slopes up and towards the side of the street, allowing adequate illumination for the drivers to see signs, pedestrians, etc. (*UN Regulation No. 98*, 2022)

> *"Passing-beam (dipped-beam) headlamp' means the lamp used to illuminate the road ahead of the vehicle without causing undue dazzle or discomfort to oncoming drivers and other road-users."*

– UN ECE, Regulation No. 48 2019

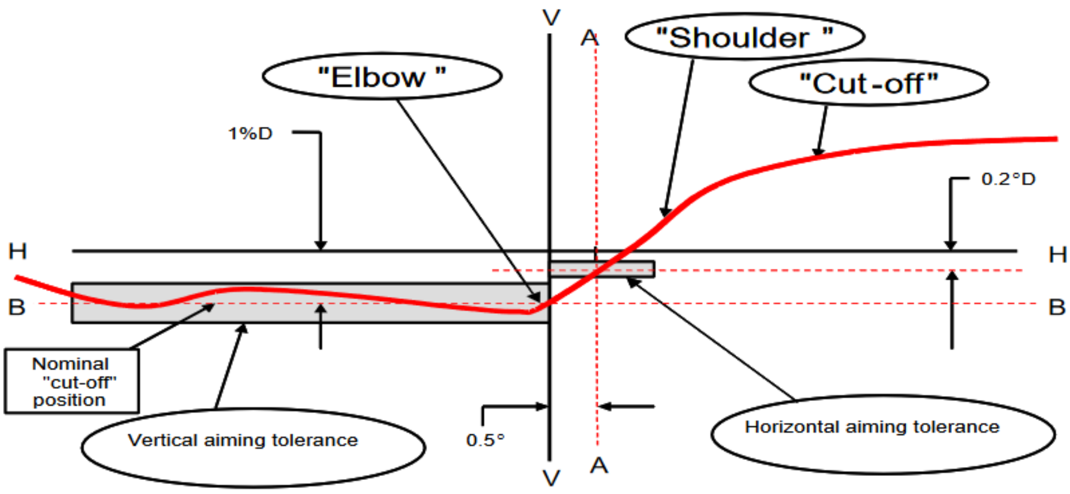

Image 1 Image of low-beam cutoff pattern. UN regulation No. 98. 2022.

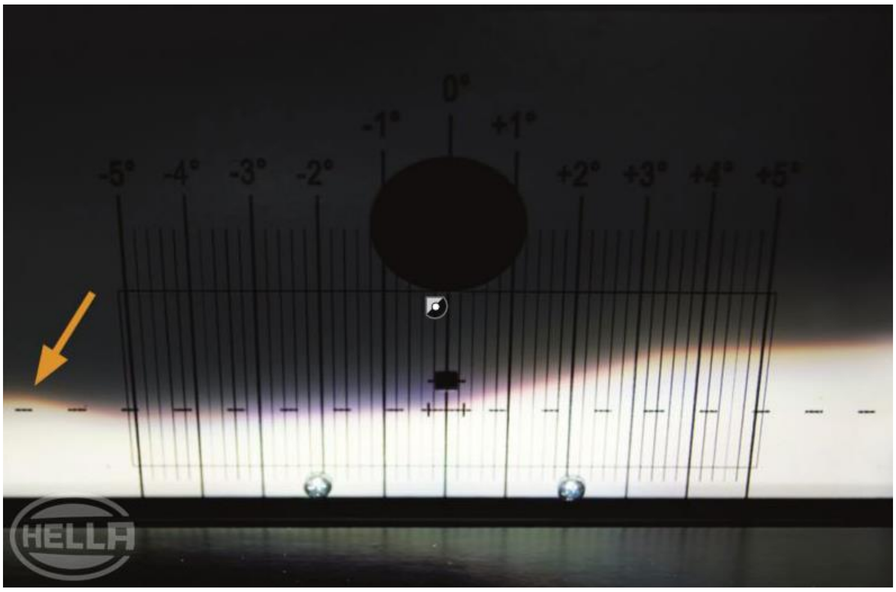

Image 2 Example of the light pattern provided by a LED low-beam headlight. Hella. 2019. (Hella.com)

High-beam headlights, also known as main-beam, driving-beam or full-beam, provide an intense, centred light beam and are used during extreme low light conditions, but should be only used if no other vehicles are in front, or if they are sufficiently far, in order to avoid disrupting other road users. The UN ECE regulations state that the driving-beam luminous intensity measured at 25 meters must not exceed 215.000 candela. (*UN Regulation No. 98*, 2022)

> *"Driving-beam (main-beam) headlamp' means the lamp used to illuminate the road over a long distance ahead of the vehicle."*

– UN ECE, Regulation No. 48 2019

Switching between low beam and high beam can be done in different ways: most commonly by using different lamps and/or light sources and alternating between them, or by changing the inclination of a single light source through motors.

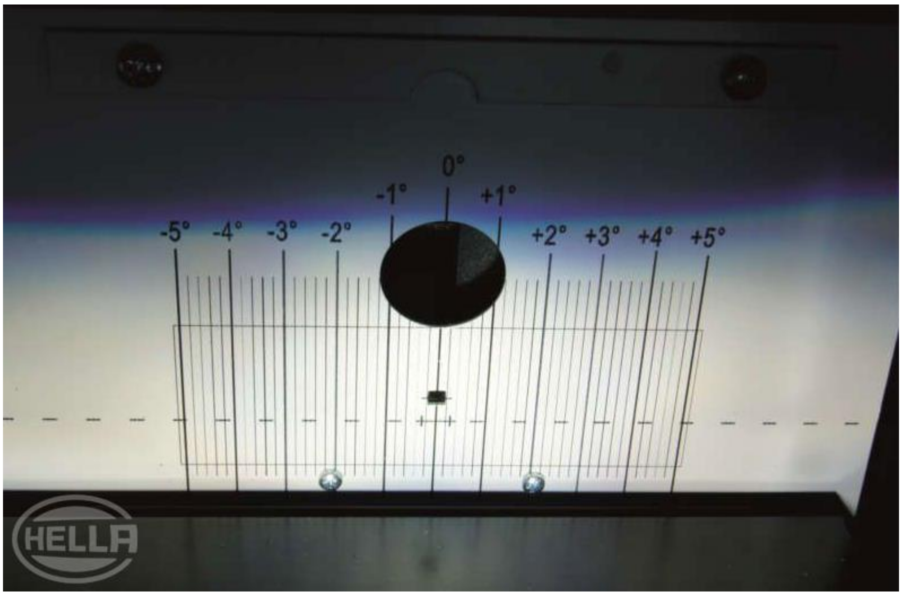

Image 3 Example of the light pattern provided by a LED high-beam headlight. Hella. 2019. (Hella.com)

3.1 Light Sources

Automobile headlamps may have different types of light sources, based on the year of the car and manufacturer choice; in this chapter, the currently used sources will be explained.

3.1.1 Halogen lamps

The tungsten-halogen lamp, known also as quartz halogen lamp, is a more advanced type of incandescent lamp. Incandescent lamps generate light when an electric current passes through a filament, which is made of a resistive material (usually tungsten, because it has a high melting point, and it does not get destroyed during the incandescence process); the heat generated during this process creates light. The halogen lamp differs from the classic incandescent lamp because the gas used inside the lamp is a halogen (either Iodine or Bromine) which prevents the bulb from blackening and slows the filament from thinning. Due to the higher pressure of halogen gas, and the higher temperatures the filament reaches, the bulb is usually made of quartz, and not of glass as classic incandescent bulbs are. In classic incandescent bulbs the tungsten filament evaporates with time and gets deposited on the glass bulb, while in the presence of halogen the tungsten atoms chemically unite with the latter and ultimately get deposited back onto the filament, this process is known as the halogen cycle (Image 4). Due to this, the halogen lamp can reach higher temperatures, creating more light.

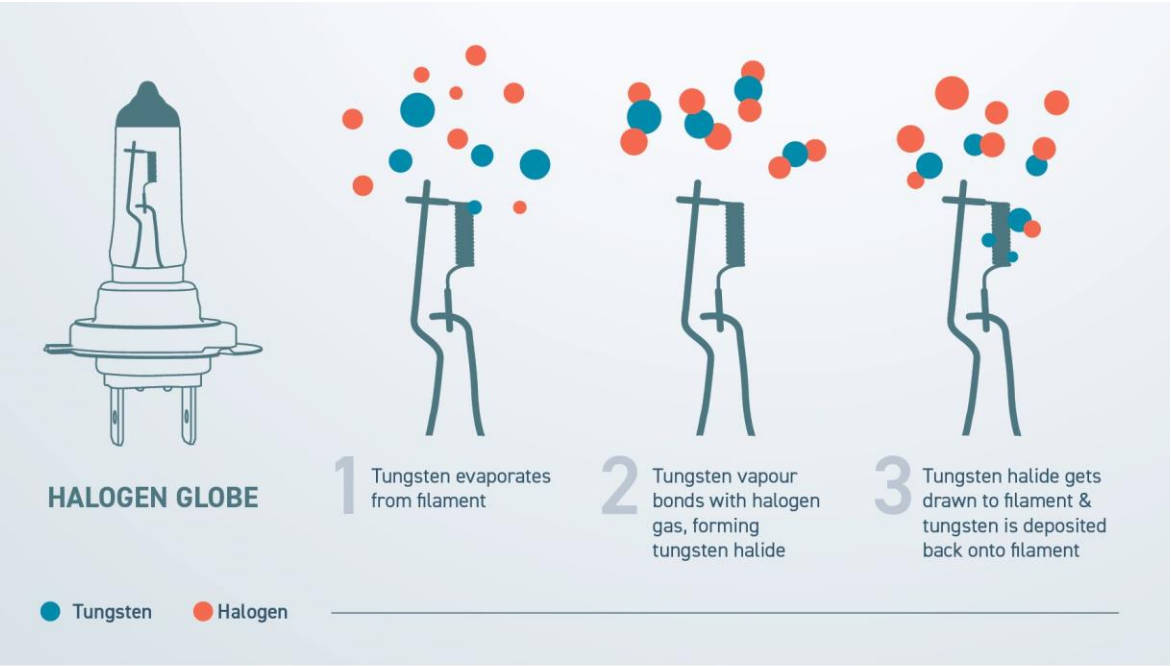

Image 4 Process of the halogen cycle. Narva. 2019. (Narva.com.au)

Generally, Halogen lamps have a colour temperature ranging from 2800 to 3400 K, appearing cooler than standard incandescent lights (from 2400 to 2800 K) and, being incandescent, have an excellent colour-rendering index (CRI) of 100. Halogen lamps are also more compact, more energy efficient and last longer than their classic counterpart, with an efficacy of 10-35 lumen per watt and a standard lamp life of 2.000 hours (range of 1.000-10.000 hours depending on the efficacy). This is a significant improvement from normal incandescent lamps that have an efficacy of 3.5-20 lumen per watt and a life of 750 - 4.000 hours.

Image 5 Example of halogen headlight bulb from OSRAM, used in vehicle headlights. (Autodoc.dk)

However, tungsten halogen lamps are far from perfect, and they have some disadvantages, especially when compared to newer types of light sources. Halogen lamps can get extremely hot, and they can cause severe burns if they are not encased in additional material (the quartz bulb surface can reach 260 °C). Additionally, the lamp is sensitive to oils, and should not be handled with bare hands, as the oils left on the surface by the hands can cause the bulb to rupture or even explode when heated. On top of that, as with all incandescent bulbs, halogen lamps are also rather inefficient: only around 8% of the emitted radiation is light, while the rest is lost as heat. Part of the emitted radiation is also ultraviolet light which can be dangerous to skin health if not properly filtered.

From the 1st of September 2018 the EU banned sale of energy intensive and inefficient halogen bulbs, in an effort to phase out the use of incandescent light sources: however, this ban does not apply to car headlights, and vehicle manufacturers may continue to use them. Nonetheless, halogen bulbs in vehicles are slowly getting phased out because better alternatives, such as LEDs and Laser lights, exist (as seen in the next chapters).

(*History of the Incandescent Light*, 2011; *Halogen Lamps - How They Work & History*, 2011; *Car lighting technology - Basic principles & lighting technology variables*, 2018; *New lightbulb rules will enable household energy savings and help reduce greenhouse gas emissions*, 2018; Gendre, 2015; Karlen, 2017; Paschotta, 2023b)

3.1.2 <u>High Intensity Discharge (HID) lamps</u>

High Intensity Discharge lamps are light sources that generate light when an electric current passes through a gas (typically either Argon or Xenon) containing the vapours of certain metals, creating a luminous electrical arc encased in a quartz arc tube. There are a variety of HID lamps that use different chemical elements, depending on the desired characteristics such as CCT, intensity, CRI; however, only one type of HID lamps is used in the automobile industry: Metal-Halide lamps with Xenon as gas. MH lamps are an improvement over typical HID lamps because there are halogens added to the gas mixture contained in the bulb that, similarly to halogen lamps, prevent the metal salts from being deposited on the quartz bulb. Additionally, newer MH lamps used in the automobile industry do not contain harmful metals such as mercury, which is sometimes still present in very small quantities in other types of HID lamps.

Image 6 Example of MH headlight bulb from BOSCH, used in vehicle headlights (Autodoc.dk)

Typically, MH lamps have a colour temperature ranging from 3000 to 4100 K, and as such, they appear colder than incandescent lights; they also have a poorer CRI than incandescent lights, ranging from 60 to 90, but this heavily depends on what types of metals are used in the bulb. On the other hand, they have a much greater luminous efficacy, ranging from 50 to 150 Lumen per Watt, and have a very long life ranging from 9.000 to 20.000 hours. Another advantage of MH headlamps is that they do not have a filament, therefore they are much more resistant to vibrations than halogen lamps, as there is no filament to break.

Similarly to halogen lamps, metal-halide lamps run extremely hot and, if they are not encased in additional protective materials, they should not be touched without proper care. Around 30% of the input power is transformed into useful light radiation, while the rest is emitted as heat and ultraviolet radiation. These UV emissions can be harmful to people and can also lead to the degradation of certain materials, therefore they are more often than not filtered out, for example by using UV-absorbing glass.

A big drawback of MH lamps is that they take some time to fully turn on from the time of ignition (like car engines), as it can take few minutes for the lamp to reach the full luminous flux output and desired colour temperature: this period is called warm-up time and the colour of the light can change substantially during this phase. These types of lamps also need a cool-down period before they can be turned on again. However, it is possible to use more advanced types of circuits and ignition systems in order to decrease warm-up and cool-down times significantly (from few minutes to one second): this is necessary in car headlights as they need to turn on and off faster. Due to the necessity of more advanced functioning systems, MH headlamps are more expensive to manufacture than incandescent headlamps. Metal-halide lamps used in vehicle headlights also have a lower lifespan due to this additional stress (compared to the same type of light sources for non-automobile uses).

Due to the higher intensity of light MH lamps can produce and to their cooler colour appearance (closer to daylight), they generally offer superior road illumination, but they can cause significant discomfort glare to the incoming drivers.

(*The Metal Halide Lamp - How it works and history*, 2012; *Car lighting technology - Basic principles & lighting technology variables*, 2018; Franke and Schöpp, 2014; Karlen, 2017; Paschotta, 2021, 2023a)

3.1.3 Light-Emitting Diode (LED) lamps

Light-Emitting Diodes (LEDs) are very compact semiconductor devices that generate light through electroluminescence, which is an electrical phenomenon in which a material emits light in response to the passage of an electric current or electric field. Basic LEDs can produce light only in a single colour, depending on the materials the semiconductor is made of. White light can be achieved with two methods: by mixing the outputs of red, green and blue LEDs or, a more expensive one, by using a single blue LED and a phosphor layer, which converts part of the blue light into longer wavelengths. A hybrid method exists, that combines both previous methods and can create higher quality light.

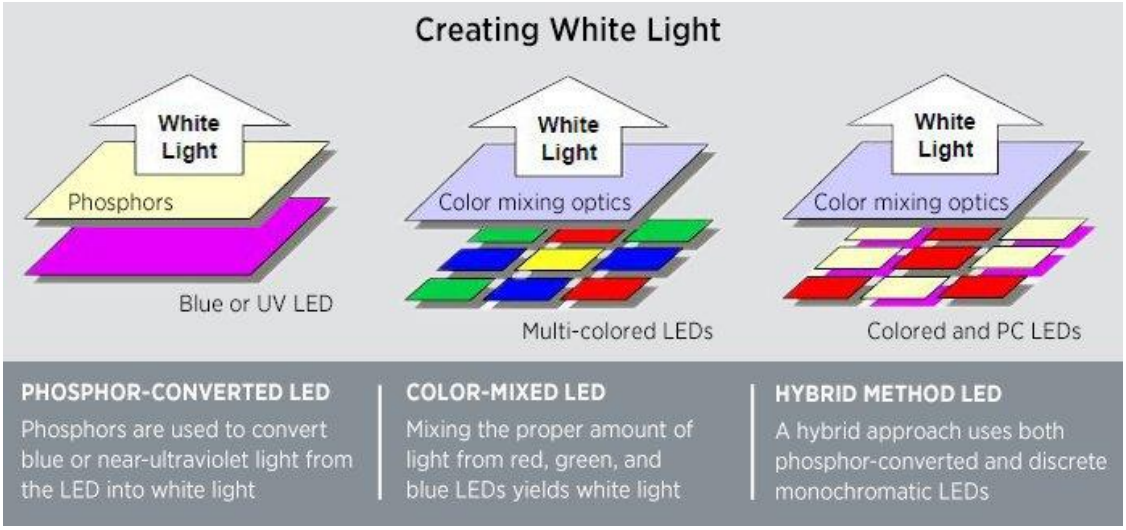

Image 7 The three different methods of creating white light with LEDs. US Department of Energy. (Energy.gov)

LEDs typically have a colour temperature that can range from 1800 to 6500 K, and a CRI of 80-95 depending on the method used to create white light. They also have a great luminous efficacy, with older LEDs at around 50 Lumen per Watt, and with newer ones that can reach over 200 Lumen per Watt. They also have the longest lifetime between illumination devices, from 25.000 to 120.000 hours.

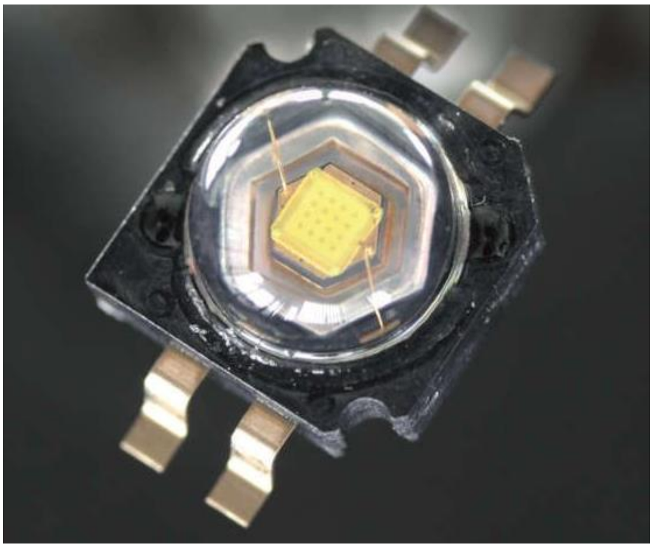

Image 8 Example of a high-power LED chip. Hella. 2018. (Hella.com)

While LEDs are a cold-light source, meaning they do not radiate heat in order to produce light, the device still can become hot due to the passage of electrical current which can damage the LED in the long run; therefore, parts such as heat-sinks (for the most demanding high-output lamps) must be installed in order to prevent overheating. Around 30-50% of the current is transformed into visible light, with the rest is released as heat. Another drawback of LEDs is that over time, the lumen output decreases, and over time the colour temperature tends to stray towards either the reds or the blues. On the other hand, LEDs are durable and shockproof, and their directional nature makes it useful for applications such as streetlighting and car lighting where stray light pollution is to be avoided.

LEDs, like MH xenon lamps, can also cause more discomfort glare for the opposite drivers due to their very compact nature and to their usually cooler CCTs.

(*LED Lights - How it Works - History*, 2012; *LED headlights for cars – function & adjustment*, 2018; Long *et al.*, 2015; Karlen, 2017; Paschotta, 2023d)

3.1.4 Laser lamps

A laser (Light Amplification by Stimulated Emission of Radiation) is a device that creates light (both visible and invisible) through stimulated emission.

Laser headlights are the newest technology in the automobile headlights field. Since laser light is mostly monochromatic, a similar technique to that of LEDs to transform blue light into white light is used in lasers: the blue laser passes through a phosphor converter, which outputs white light.

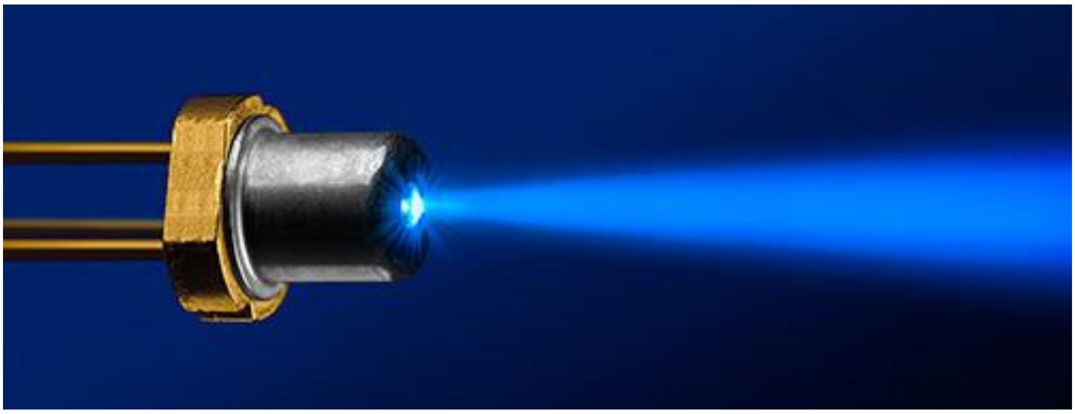

Image 9 Blue laser light source, which will then be converted to white light thanks to the phosphor layer. OSRAM. (Lasercomponents.com)

The currently available laser headlights have a colour temperature ranging from 4100 K to 5500 K (but some tuneable prototypes achieve a range of 2800 K - 4000 K), CRI of 78-88 and an excellent luminous efficacy, ranging from 170 to 420 lumen per watt. They can produce a near-parallel high-beam that can reach up to 600 meters, more than twice as much as halogen, HID and LED headlamps. They are also very compact, even more than LEDs, giving ample freedom to headlight designers. Laser headlights also do not produce excessive heat, unlike classic headlights such as halogen or HID, and they produce even less heat than LEDs. They have a lifespan of 20.000 to 50.000 hours. The power conversion efficiency of a laser is around 50%, with up to 70% for the most advanced lasers (numbers may be lower due to the presence of the phosphor layer). Another benefit of laser diodes is that they are even more compact than LED chips, meaning that headlights can be designed to be even smaller, giving ample design freedom to car manufacturers.

The main drawback of laser headlights is that they are a new technology, therefore they are very expensive to produce, and cheaper phosphor converters are not heat-resistant, therefore driving the prices up even more. Furthermore, due to their very high light intensity and small size, laser lamps may also cause more discomfort glare for oncoming drivers.

(Kanskar, 2005; 'BMW develops laser light for the car', 2011; *Laser light in the car industry: Questions and answers on innovative laser technology | OSRAM Automotive*, 2019; *Laser light for headlights: latest trend in car lighting | OSRAM Automotive*, 2019; Tseng *et al.*, 2019; Y. P. Chang *et al.*, 2019; Y.-P. Chang *et al.*, 2019; Fang *et al.*, 2020; Wu *et al.*, 2020; Donati *et al.*, 2021; Paschotta, 2023c)

3.1.5 Comparison of headlamp light sources

	Working Principle	Luminous Efficacy (lm/W)	CCT (K)	CRI	Lifespan (hours)*	Conversion Efficiency**
Halogen	Incandescence	10 - 35	2800 - 3400	100	2.000	8%
HID (MH)	Gas Discharge	50 - 150	3000 - 4100	60-90	9.000	30%
LED	Electroluminescence	50 - 200	1800 - 6500	80-95	25.000	30-50%
Laser	Stimulated Emission	170 - 420	2800 - 5500	78-88	20.000	50%-70%

*Table 1 Comparison of light sources. Self-produced. 2023. *Lifespan of car headlights **Input current transformed into visible radiation*

In general, the most used light sources in car headlights are halogen, HID and LED; however, due to the poor efficiency and lifespan of halogen lamps, halogen headlights are getting phased out, and older cars are often getting retrofitted with HID or LED headlamps. The slight loss of CRI compared to halogen is not a significant issue, because achieving a perfect colour appearance is not necessary in the case of the automobile industry. However, it should be noted that a high CRI is still important, because a lower CRI can decrease visual comfort and object recognition.

Concerning the luminous efficiency, CCT range and lifespan, halogen is clearly the worst performer, while LEDs and lasers are the best overall. Metal-halide lamps are still a good choice for car lighting, despite some of their shortcomings, because they are cheaper to produce than LEDs and Lasers, and they have a luminous efficacy comparable to LEDs. Both halogen and MH headlamps have lower lifespan compared to their counterparts for use in non-automobile settings, this is because of the added stress these light sources experience during use.
For example, a study conducted in 2011 found evidence that halogen lamps lose around 31% of their lifespan when they are turned on and off multiple times versus when they are continuously running. (Cho and Kim, 2011)

Overall, with the global trends of energy savings, it is clear that future technologies will concentrate more on LED and Laser light sources: they may be more expensive to produce, but they have remarkable lifespans, efficiency, provide higher illumination ranges and are more versatile. Furthermore, the more common a technology gets, the cheaper it becomes, owing to the process of manufacturing becoming faster, easier and more efficient.

3.2 Optical systems

While there are many ways in which the light from a headlamp cand be focused, they work with two basic principles: refraction and reflection; by using both of these principles a third hybrid type of optical system is created, known as projection system.

Refraction is the redirection of light as it passes from one medium to another (in this case, lenses) with a different refractive index. In the context of car headlights, the primary purpose of refraction is to focus and direct light in a specific manner to illuminate the road ahead effectively.

Reflection is the redirection of light in its original medium when it encounters a surface that does not absorb the rays of light. Regarding car headlights, the main purpose of reflection is to efficiently collect the light and direct it on the road ahead.

Projection systems incorporate both elements and are usually more precise and more efficient, but due to their nature they take more space.

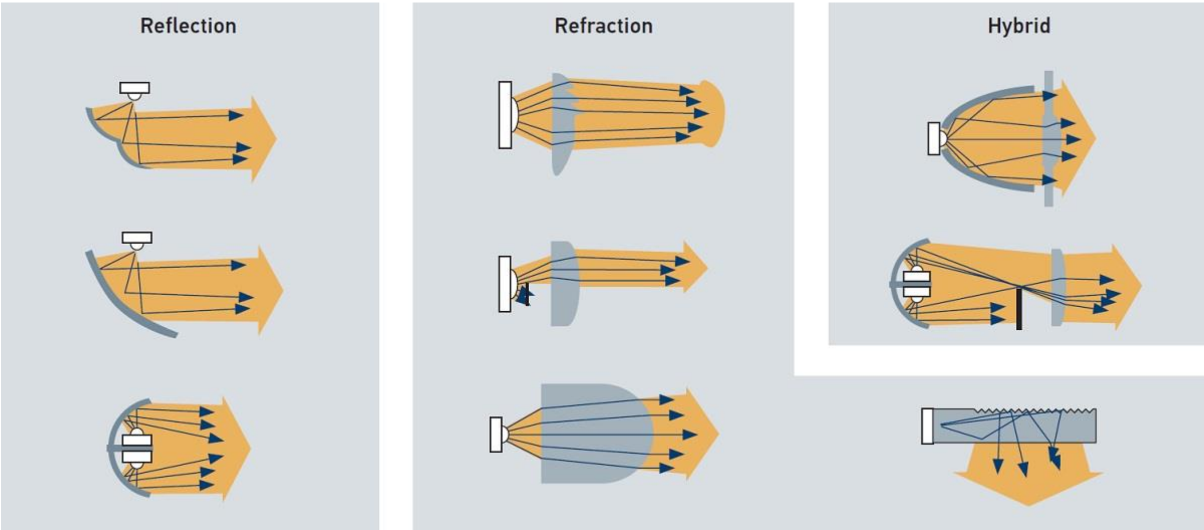

Image 10 The different methods of redirecting light, in this case coming from a LED source. Hella. 2018. (Hella.com)

Lenses are transparent optical components designed to manipulate the light by using the phenomenon known as refraction. They are typically made of glass, however, for usage in car headlamps they are usually made of polycarbonate, due to its impact strength, lower density, heat resistance and ease of moulding. Lenses are positioned in front of the light source and reflector, and they are responsible for further shaping and directing the light, thanks to their carefully designed shapes and patterns.

Reflectors are curved surfaces positioned behind the light source that capture the light emitted by the light source and redirect it in a specific direction; they are designed to reflect the maximum amount of light forward, enhancing the efficiency of the headlight system. The most commonly used types of reflectors are parabolic, free form, ellipsoidal and hybrids.

Parabolic reflectors (Image 11) are the oldest type of reflectors and have the shape of a paraboloid, which is a surface generated by the rotation of a parabola around its axis. The light source is positioned in the focal point of the paraboloid, and the light radiating upwards is reflected downwards on the road ahead of the car. The optical cover lens of this type of reflector further shapes the beam in order to meet legal requirements. In this system, only about 27% of the light from the source is useable light. These reflectors are rarely used anymore nowadays.

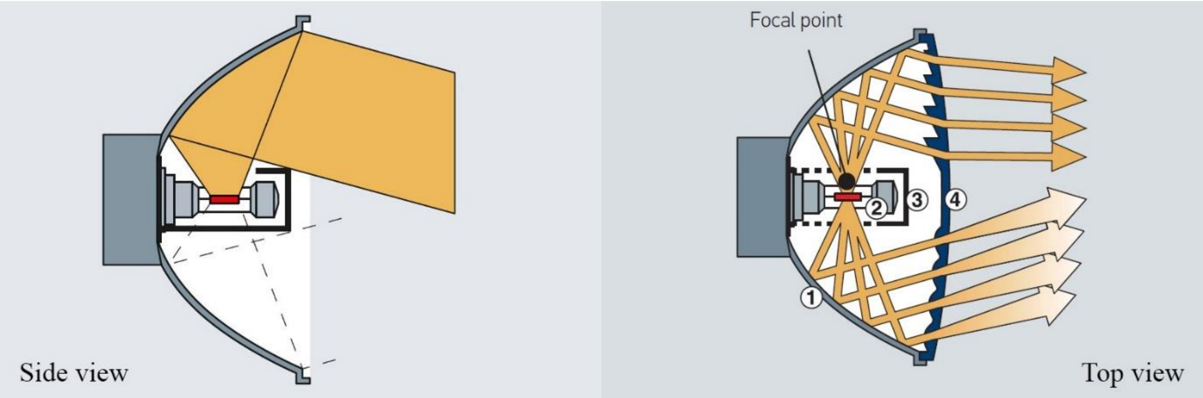

Image 11 Side view and top view of a Parabolic headlamp. Hella. 2018. (Hella.com)

Free form (FF) (Image 12) reflectors have freely formed shapes that can only be calculated and optimised with the aid of computers due to their complexity. They are more efficient because the whole reflector surface can be used to redirect the light towards the road: the light source is positioned in the focal point and both upwards and downwards light is used to create the beam. Thanks to their precision, the presence of optical lenses is often not necessary. This technology is more efficient, with around 45% of the light being useable light. Most cars use this type of reflectors for their low-beam headlamps.

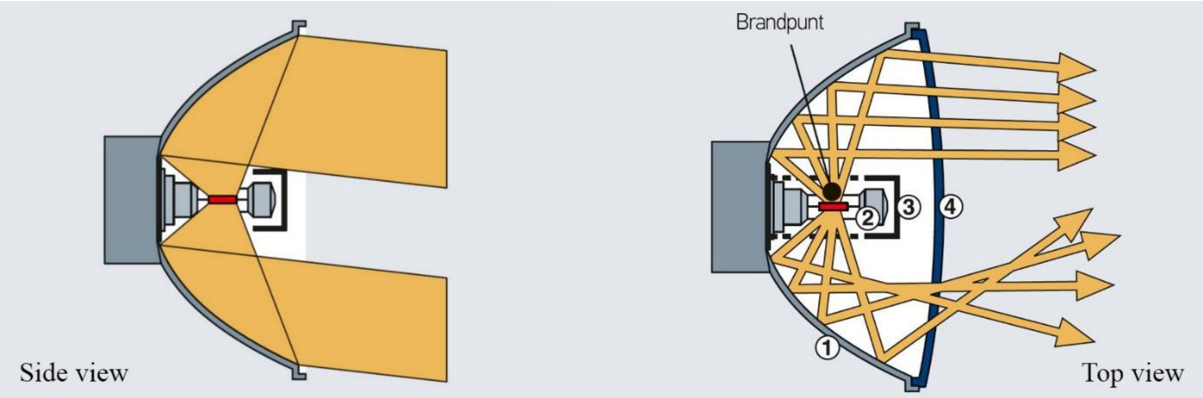

Image 12 Side view and top view of a Free-form headlamp. Hella. 2018. (Hella.com)

Ellipsoidal (DE) reflectors, or ellipsoidal projectors, have the surface of a triaxial ellipsoid, which is a surface that can be obtained with the deformation of a sphere on all three axes (all axes must have a different length). The light source is placed in one of the focal points of the ellipsoid, the reflective surface then redirects the light towards its secondary focal point, where part of it gets stopped by a shield in order to create a sharp cut-off; the light then gets projected onto the road thanks to a lens. Approximatively 36% of the source light is useable light.

Hybrid reflectors combine multiple reflector designs and elements to achieve better beam patterns and efficiency. One example of hybrid reflectors is the super DE (Image 13) projection system: it functions with the same principles as ellipsoidal projectors, but the reflective surface is a free form reflector designed with the aid of computers, which increases its efficiency. The useable light amounts to around 52% of the source light.

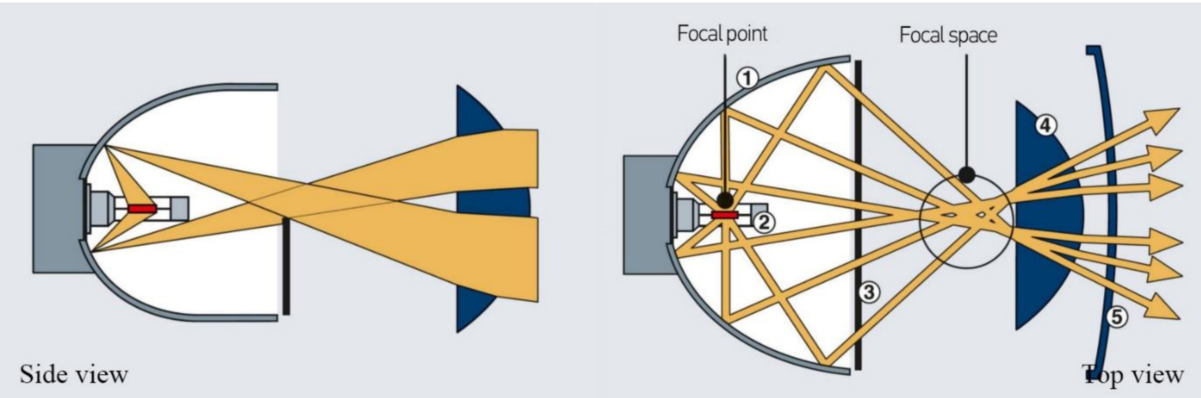

Image 13 Side view and top view of a Super DE headlamp. Hella. 2018. (Hella.com)

Other hybrid types include the bifocal reflector, which is a reflector that uses two reflector sections with different focal points, and the homifocal reflector, which is a reflector with different sections that have a common focal point. (*Headlight (Automobile)*, 2011; *Physics Tutorial: Refraction and the Ray Model of Light*, 2014; *Physics Tutorial: The Law of Reflection*, 2014; *Physics Tutorial: Boundary Behavior*, 2014; *Headlight lens components, types & regulations*, 2018; *Hella Headlamp Systems*, 2018)

4. MAIN BODY

4.1 Automobile headlights functions

Automobile headlights are the front-facing light of a vehicle that are used to properly illuminate the road ahead during low-light conditions due to weather or time of the day. Their purpose is to enable drivers to see the road ahead, gauge its width, and identify any possible obstacles; but also to be seen by other cars. Car headlights incorporate different types of auxiliary lights: the units that are tasked to illuminate the road are known as low-beam and high-beam headlamps. Switching between low-beam and high-beam is done by using different lamps, or by using a single lamp that can either move up and down through motors or through a system that can shape the beam of light.

As mentioned in the previous chapters, headlamps may contain different light sources such as halogen, metal-halide, LED, and laser and may shape the beam with lenses, reflectors, and projectors. Modern cars also have sensors that are activated based on certain factors (such as speed, steering angle, ambient lighting conditions, weather conditions, GPS data) and can activate or deactivate the high-beam, rotate the headlamps towards the steering direction or, on the most advanced system, even change the light beam's distribution.

Headlights are considered important safety devices and therefore are required to meet international laws to ensure they have good safety standards. When it comes to design, car headlights face many challenges: they must meet strict laws while providing good glare-free illumination and also fit the design aesthetics of the car. Producing a good headlight involves a lot of research and good knowledge of lighting, optics, and material physics. Due to these challenges, design or age-related problems may occur.

4.2 Common problems

The most common problems in car headlights are poor performance and glare; both of these issues can be caused by different factors such as headlamp misalignment, age, dirt and poor maintenance. However, these two issues are two sides of the same coin: generally, to improve performance one must increase the brightness of the light source, which can actually lead to increased glare. This is a dilemma that has been existing since the creation of cars. In this chapter, both of these issues will be explained and analysed; the findings will be then used for the final solution.

4.2.1 Poor performance

One common issue in car headlights is poor performance, meaning that the headlights are either too dim, have poor light distribution, inadequate reach, or all of the previously mentioned. For example, according to a test for headlight effectiveness conducted in 2016 by The Insurance Institute for Highway Safety (IIHS) on 31 models, only 12 achieved acceptable scores: the worst performer, the BMW 3 series, illuminated only 40 meters ahead with its halogen low-beam headlight, while the best performer, the Toyota Prius V, illuminated 120 meters ahead with its LED low-beam headlight. (Mays, 2016; *Headlight performance*, 2022)

> *"The IIHS rates headlights based on two criteria: visibility and glare. For visibility, headlights with a good rating illuminate the road's right side by at least 325 feet (99 meters). Those with a poor rating illuminate only the right side of the road by 220 feet (67 meters) or less. The IIHS also deducts points when headlights temporarily blind other drivers."*

- (Sadie, 2021)

IIHS ratings have also been correlated with night-time crash rates: good headlight systems were associated with the greatest crash rate reductions. (*Good IIHS headlight ratings linked to lower crash rates*, 2021; Brumbelow, 2022)

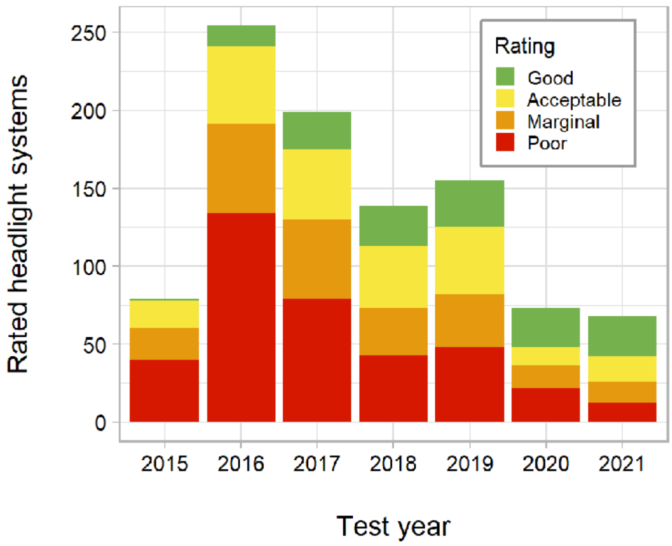

Image 14 IIHS headlight ratings by test year. Matthew Brumbelow. 2022.

This relatively common issue can cause difficulty for drivers to properly detect obstacles, pedestrians or animals on the road and therefore increase risk of accidents. Furthermore, inadequate luminous intensity, distribution and/or reach can make it harder for drivers to judge distances and react quickly to changes in road conditions. Poor luminous intensity may also result in drivers being forced to drive with their high beams on, which can cause glare on oncoming vehicles.

The lack of adequate headlights is a serious safety issue that can severely impact drivers, other road users and animals. It is particularly important to understand the causes of a car's headlights poor performance in order to increase road safety.

While some causes may be due to design errors and poor aim from the manufacturer as previously stated by the IIHS, there are also other possible causes. These causes may be age-related, such as worn-out bulbs, dirty or damaged headlight lenses, electrical problems, and / or misaligned headlamps: it is important to detect such issues as soon as possible and find replacements.

Other causes may also be due to improper or illegal modifications: when changing the light source in a headlamp it is important to use the exact same light source as headlights have complex designs that are made only for one type of light source. For example, it is recommended to change the whole headlamp when going from halogen to HID or LED, as the optical system of a headlight unit will not create the right beam intensity and pattern with a different type of light source and will end up have poor performance. (*Xenon headlights – function and retrofitting*, 2018)

A Czech study conducted for an extended period of time and published in 2015 states that "*Out of the pedestrians fatally injured in a traffic accident annually, over 60 % were killed at night (comparison shows a significant difference between daytime and night time traffic density), thereof approximately 90 % fatal accident took place on rural roads, i.e., roads without public lighting.*" (Bradac *et al.*, 2015)
These types of studies are important because they show us how significant having good headlights is, and how many accidents can be avoided by incorporating newer technologies in vehicles, in order to complement poor or non-existent street lighting.

Many times a driver is forced to use the high beam headlights in order to properly see the road, especially at higher speeds, as a lot of cars have poor range on their low beam headlights: this causes problems such as glare for oncoming drivers, and also other road users or animals. An obvious solution to this would be to have better street lighting in order to avoid people using high beams too much and instead sticking to low beams only. However, this is not a feasible solution as good street lighting is not possible everywhere as budget, ease of maintenance, traffic of the road, animal presence are some aspects to be considered when planning street lighting.

4.2.2 Glare

> *"Condition of vision in which there is discomfort or a reduction in the ability to see details or objects, caused by an unsuitable distribution or range of luminance, or by extreme luminance contrasts."*

- (CIE, International Lighting Vocabulary, 2nd edition, 2011)

Glare is one of the most frequent problems when it comes to car headlights. There are two types of glare: discomfort glare is glare that causes discomfort while not necessarily impairing vision, while disability glare is glare that impairs the visions of objects without necessarily causing discomfort.

Image 15 Photograph of a car's front headlights, causing glare. RAC. 2022. ([Rac.co.uk](Rac.co.uk))

Discomfort glare is caused by an intense light that produces subjective distress and it is often measured with the DeBoer scale, which goes from 1 to 9, with the lowest number meaning that the discomfort caused by the glare source is unbearable for the observer. The main factors of discomfort glare are the relationship between the luminance of the light source and the background luminance, the apparent size of the light source, and the position and angle of the light source relative to the observer's line of sight. (Mace *et al.*, 2001)

Disability glare is caused by an intense light that decreases the observer's ability to perform visual tasks: this intense light scatters inside the eye, creating a "veiling" effect that reduces the ability to recognise other objects and lights in the line of sight. The main factors of disability glare are the illuminance on the eye (measured in lux, perpendicular to the line of sight), the angle between the line of sight and glare source, and the age of the observer. The age of the observer is an important aspect because stray light in the eye is caused by many factors such as scattering, diffraction on the pupil and eye imperfections (that become more common the older the observer is). (Mace *et al.*, 2001) This is why in many experiments older test participants seem to be more aware of the impacts of glare than their younger counterparts.

Glare in vehicles is usually due to extreme luminance contrasts: if the road is dark, other headlights may cause glare due to this great difference between the intense headlights and the dark surroundings. As mentioned in the previous chapter, good street lighting can mitigate the issues associated with both poor visibility and glare, as a strong light source causes less glare when the background luminance is higher. However, having good street lighting is not possible everywhere, and even if this could be the most desired and simplest solution, it could have negative impacts on light pollution and biodiversity. Therefore it is important to also find and apply solutions to the vehicles themselves.

Glare, as mentioned in the introduction chapter, has always been an issue in vehicles, but its frequency increased in the past decade due to the introduction of new lighting technology such as metal-halide and LED sources. While these new sources have great efficiency and can illuminate the road better and further, they may also pose increased risk of glare.

This issue appears to be quite widespread: according to a RAC (an UK-based automotive services company) survey of 2700 UK drivers, 89% of the respondents think car headlights are too bright, with 88% of them saying that they get dazzled by them while driving. The most concerning finding of this research, however, shows that 65% of the dazzled drivers take between one and five seconds to see clearly again, while 12% said it could take upwards to six seconds to fully recover: this is important knowledge, because depending on the speed of the car, even one second could be the difference between avoiding or not an accident. (*Blinded by the lights – nearly one-in-four drivers think most car headlights are too bright*, 2022)

Another similar study, conducted in the Czech Republic, found that 25% of drivers experience glare almost daily, 30% experience glare at least once a week, 24% at least once a month and 18% several times a year, with only 3% almost never experiencing glare. (Viktorová, Mičková and Stanke, 2022)

A study conducted on headlights of most common cars in Iran also found that, when the background luminance was as low as 1 cd/m2, the glare caused by high-beam headlamps exceeded the recommended disability glare thresholds of all age groups, while the low-beam caused disability glare only at closer distances. (Mehri *et al.*, 2021)

According to a 2016 test conducted by the IIHS many vehicles don't reach a good rating (*New ratings show most headlights need improvement*, 2016), but thanks to the IIHS statistics some manufacturers have been encouraged to improve their headlights. (*IIHS award criteria push manufacturers to scrap inferior headlights*, 2020)

There are multiple factors that can influence glare in headlights: the luminous flux, the position, the angle, the size of the glare source, and the state of the headlights (age, dirt). The main causes of glare in headlights are the intensity of the luminous flux and the angle of the glare source relative to the viewer's line of sight. A study from the National Highway Traffic Safety Administration (NHTSA) in the USA also found that the higher the mounting height of headlights, the higher the glare intensity is, both for discomfort and disability glare. (Akashi, Rensselaer Polytechnic Institute, and National Highway Traffic Safety Administration, 2008)

However, even headlights that are considered good can create glare due to age and dirt. For example, the lamps' angle can eventually deviate from the ideal angle, leading to increased light coming onto the oncoming driver's eyes. Dirt and dust can also make it so the light beam strays from the intended path: this can cause the light to shine in the wrong directions. Finally, age may darken the protection lens of the headlight (which nowadays is usually plastic) and distort the light beam, which can either cause poor visibility, excessive glare, or both.

The vehicle's pitch can also influence glare, for example if the vehicle has extra load, or the state of the road forces a change in pitch on the whole vehicle. This change in the vehicle's pitch can cause the headlights to actually shine at a higher level, possibly causing glare to other drivers in front of the vehicle in question. On the other hand, the pitch can also cause the headlights to shine at a lower level, directly onto the road, causing poor visibility due to the decreased beam range.

Nonetheless, these issues can be fixed or mitigated with newer technologies, such as self-cleaning and self-levelling headlights. (*Headlamp cleaning system: Faults, testing*, 2018; *What are self-levelling headlights?: Function & check*, 2018). The UN Regulation No 48 now requires an automatic levelling device that can automatically change the pitch of the headlamp, but only if the headlights has a light source that emits a luminous flux of more than 2000 lumen. ('Regulation No 48 of the Economic Commission for Europe of the United Nations (UNECE)', 2019)
However, it can be argued that automatic levelling devices should be used in any car, and not only on vehicles which headlights emit a luminous flux of more than 2000 lumen, as glare can be caused even by weaker light sources. To support this, a study shows that having a dynamic headlight levelling device (dHLD) on every car is more beneficial than having this requirement only on certain vehicles. Furthermore this study also recommends these requirements to be revised and to be more accurate, as they are superficial and don't account for many parameters than are vital for a good HLD. (Kosmas, Kobbert, and Tran Quoc Khanh, 2020)

For cars that do not have these newer features yet, it is important to have regular check-ups with a mechanic in order to properly adjust the angle of the headlights, to clean or change aged and/or dirty cover lenses and to replace any component that may cause distortions in the light beam.

Due to the fact that newer lights, such as HID and LED, appear whiter or even bluer to our eyes compared to the classic halogen bulbs has also introduced new problems: not only are they capable of a higher luminous intensity, but also their bluish appearance may create even more discomfort glare. In a study conducted on twelve participants in 2005 on the blue content of car headlamps and discomfort glare (using the De Boer scale) found that both HID and LED tend to create more discomfort glare than the halogen counterparts, with HID creating only slightly more discomfort, while LEDs becoming unbearable the colder and more intense the light got.
In this experiment the researchers used five different types of reflector-based lamps: tungsten-halogen, HID, and LEDs with three different CCTs (4000, 4800, 6600 K). The test participants were seated in a car, in pairs, and were asked to rate their discomfort after being exposed to illuminances of 0.25, 0.5 and 1 lux (for each lamp type) produced at the eyes of the participant. This test was conducted during the night and the only light sources were the test lamps, and the test vehicle's own tungsten-halogen low-beam headlights, with the ambient light averaging 0.20 lux. Each pair was exposed to the test light for three seconds, and each lamp order was randomised (most likely in order to not create a pattern, as going from warm to cold lights may seem "worse" than going from cold to warm lights). The experiment findings were correlated to previous evidence that bluish light creates more discomfort glare than white light. (Sivak, 2005)

It is important to note that LEDs do not necessarily create more glare, but since most LEDs use in new vehicles have a cooler colour appearance, they have a tendency to create more glare. In fact, in a similar experiment conducted by Sullivan and Flannagan in 2001, three different types of tungsten-halogen lamps (a standard tungsten-halogen lamp, a blue-tinted lamp, and a neodymium-filtered blue-tinted lamp) were compared for their discomfort glare rating (using the De Boer scale). The results showed that the blue tinted lamps created more discomfort glare, especially at higher illuminances, than the unfiltered tungsten-halogen lamp. However, as the researchers stated, there is empirical evidence that bluish light causes more glare, but the quantitative nature of this relationship still remains unclear. (Sullivan and Flannagan, 2001; Sivak, 2005)

It is important to note that the blue content in a light source’s spectrum significantly influences discomfort glare, but it has little to no impact on disability glare. However, the illuminance at the eye was the most important factor in both discomfort and disability glare ratings. (Van Derlofske *et al.*, 2004)

Avoiding glare is vital because exposure to intense lights can cause eye strain, and can also cause temporary and, in certain cases, permanent effects on the eye, especially if one already has eye imperfections. (van Norren and Vos, 2016; Joshua Dunaief, 2023)

On top of that, glare can lead to fatal outcomes; both discomfort and disability glare are dangerous as the former can influence the driver’s attention and reaction times, while the latter can veil for few seconds the presence of other vehicles and obstacles onto the road. In fact, according to the RAC, 300 accidents per year in the UK are being caused by headlight glare. (Cox, 2023)

“At the age of 18 it takes less than one second to recover from glare, at 65 it can take up to nine seconds.”

- (Cox, 2023)

4.2.2.1 Glare survey

In order to fully understand how widespread the problem of glare is, and have more recent opinions, the author conducted an online survey about headlight brightness perception and glare, for both drivers and pedestrians. The survey was conducted on Google Forms and was spread throughs social media such as LinkedIn and Facebook. Out of 88 respondents, 2 of them were not drivers, therefore they left the driving portion blank.

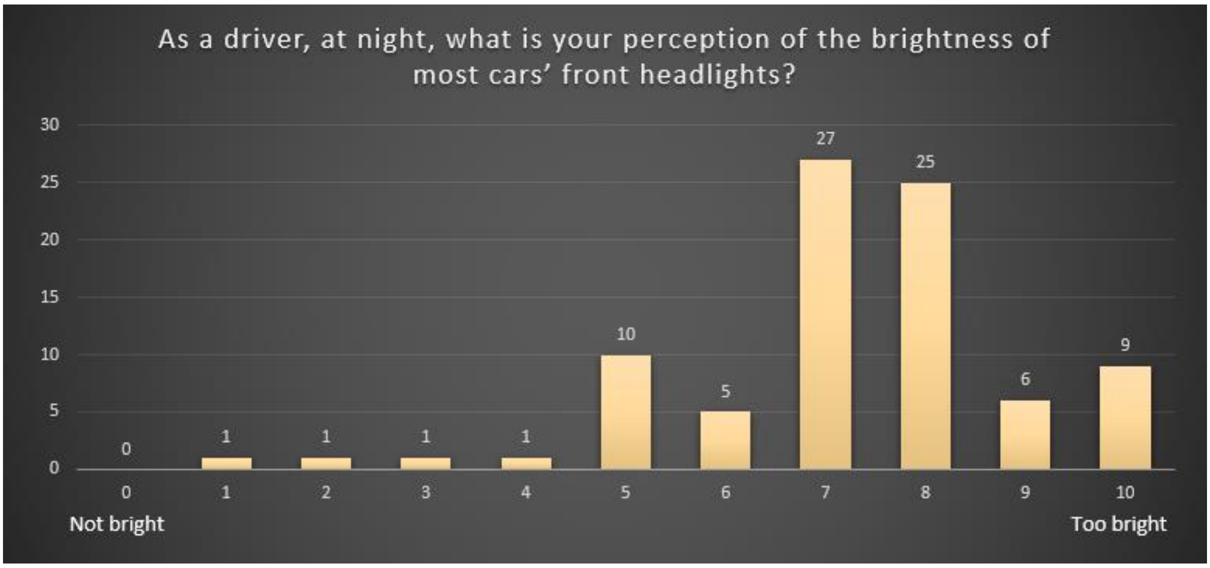

Table 2 Drivers' perception of cars' headlights. Self-produced. 2023.

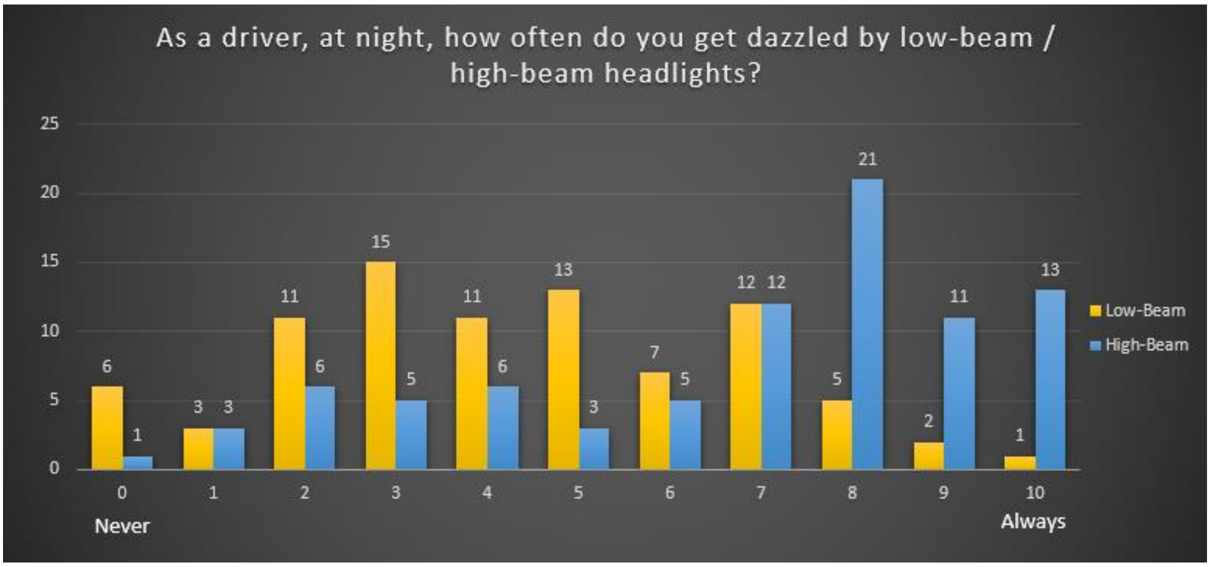

Table 3 Comparison of low-beam and high-beam occurrence of glare according to the survey respondents (drivers). Self-produced. 2023.

According to the survey, a majority of drivers (84%) think that most cars have too bright headlights and around 31% of the respondents are dazzled often due to low-beam headlights, while high-beam headlights are dazzling more than double of the respondents, with 72% stating they often get dazzled (Table 2 and 3).

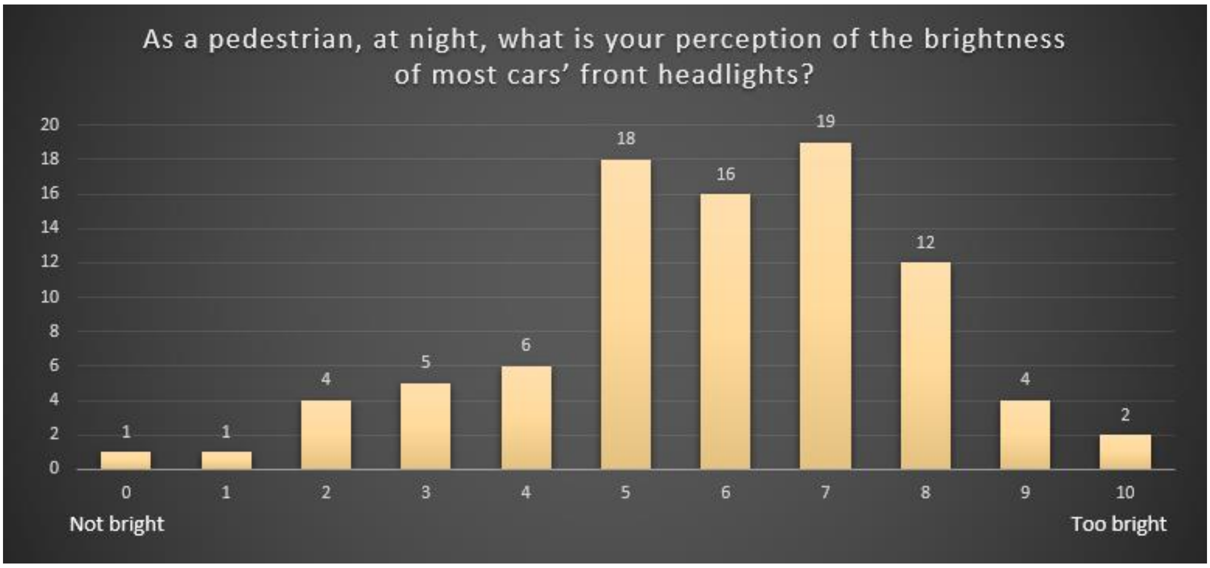

Table 4 Pedestrians' perception of cars' headlights. Self-produced. 2023.

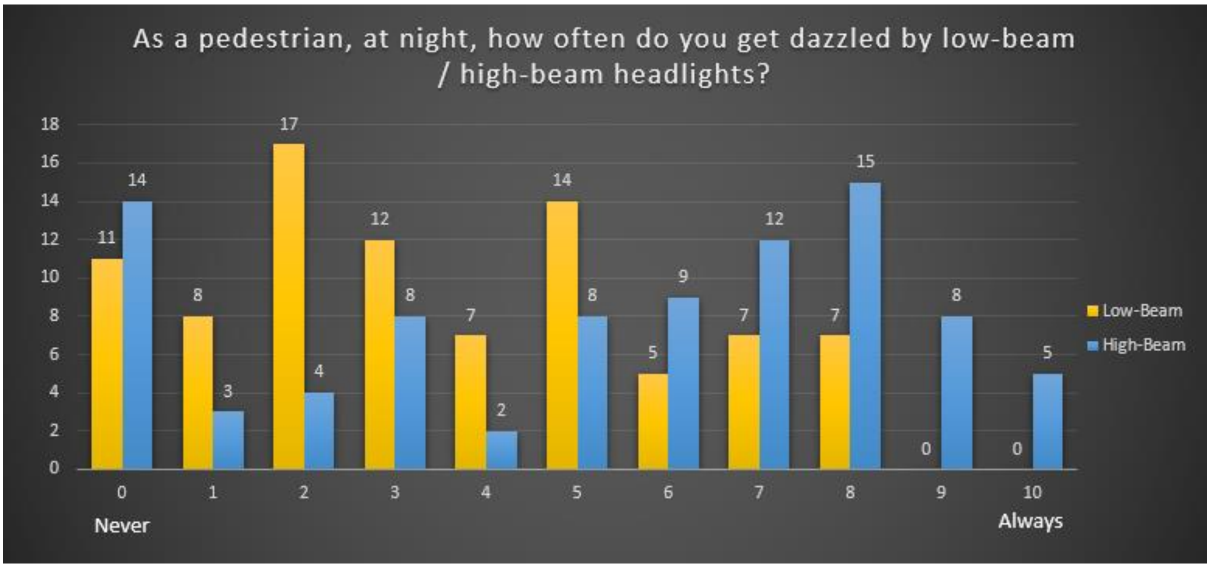

Table 5 Comparison of low-beam and high-beam occurrence of glare according to the survey respondents (Pedestrians). Self-produced. 2023.

On the other hand, pedestrians seem to be affected less by cars' headlights' brightness, with 60% stating that the headlights are too bright, with only 22% being dazzled by low-beam and around 56% being dazzled by high-beams (Table 4 and 5).

While these numbers are lower than the drivers' results, they are still affecting a significant portion of pedestrians. These numbers are consistent with the author's predictions because headlights are usually aimed at the road ahead, therefore headlights have a greater effect on drivers than pedestrians: it is also important to note that the consequences of glare are also greater on drivers, as they travel at much greater speeds and even few seconds of dazzling may have dire consequences.

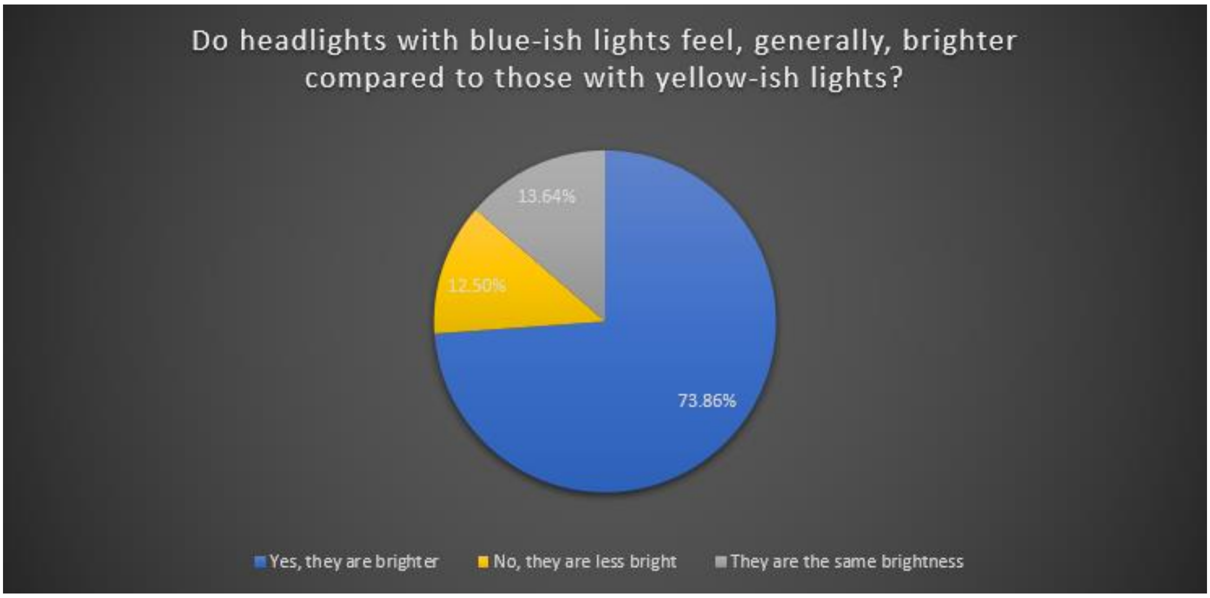

Table 6 Perception of brightness depending on the colour appearance of the light. Self-produced. 2023.

Additionally, it appears than most respondents perceive colder lights (blue-ish) to be brighter compared to warmer ones (yellow-ish); this can be due to different factors, such as the fact that newer lights that most often have a higher CCT, therefore appearing blue-ish to our eye, are usually capable of much higher luminous intensities, or due to the fact that our eyes are more sensitive to that particular range of wavelengths, possibly because they are also the most damaging to the eye. (Ouyang *et al.*, 2020)

4.3 <u>State of the art</u>

As mentioned in the previous chapters, technologies to mitigate the most widespread problems such as poor performance or excessive glare already exist; however, many cars still don't have them included, but some car manufacturers are developing extraordinary technologies for their top-of-the-line cars that, with time, could revolutionise vehicle lighting. In this chapter, some of these technologies will be shown and explained, in order to use them as starting point and inspiration for further solutions.

Before going in depth with the newest technologies, it is important to mention that many cars nowadays have adaptive headlights, which mitigate some of the issues mentioned previously, but they do not eliminate them as efficiently as the newest highly advanced headlights. Nonetheless, they function with the same principles: by smudging the lines between low-beam and high-beam headlights; many adaptive headlights systems can create different light beams in order to help the driver navigate different situations, with the use of auxiliary light sources (which are integrated into the main headlamp) and advanced optical systems.

For example, HELLA developed an Advanced Frontlighting System (AFS) (Image 16) that can create different light beam patterns through a free-form cylinder positioned between the light source and the lens: this cylinder has different contours that change the light distribution on the road, depending on the rotation of the cylinder, and offers seven different types of beam. Depending on the speed of the vehicle, steering angle and weather situation, different types of light distribution will be created by this system. (*Adaptive headlights – AFS Lights*, 2018)

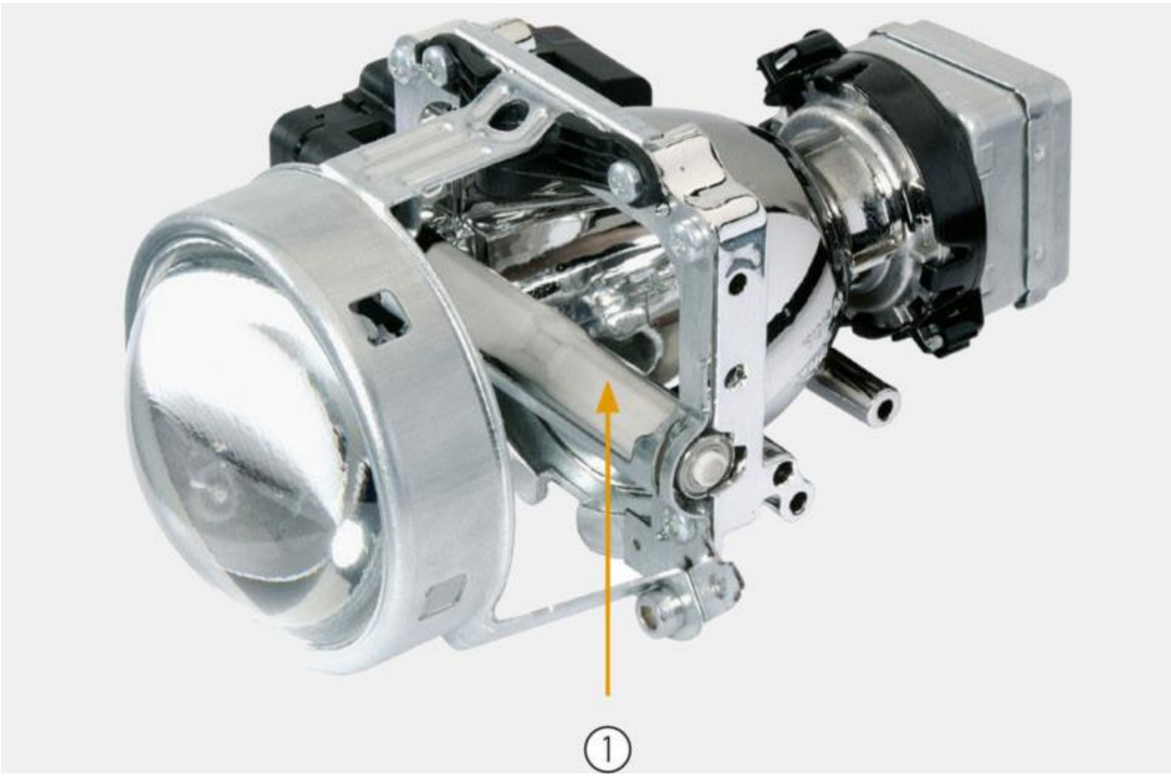

Image 16 Hella's AFS, with the free-form cylinder (1) shown in the middle. Hella. 2018. (Hella.com)

Certain cars also use GPS data, paired with predictive systems, in order to better illuminate the road and to guide the driver. This system also works when little or no data is available, by compensating it with camera sensors and the position of the steering wheel. Depending on the location, different types of beam will be produced; for example, when the car is coming close to a roundabout, the beam will widen in order to illuminate the surrounding area better. (GNSS, 2021)

These new technologies are considerable improvements over the “classic” types of headlight technologies, which only offer two types of beam (low and high) and may sometimes complement their shortcomings with auxiliary light such as fog lights and other types of lights. It is easy to notice that thanks to advancements in technology and computing a trend in car lights is being delineated: the differences between low and high beams are becoming increasingly minor, as these modern technologies are applying the strengths of one to the shortcomings of the other, and vice versa.

Soon we would probably stop using low and high beam in our vocabulary due to the introduction of “hybrid” beams that can act as both, and do even more, rendering the former obsolete. In the following section, some more advanced technologies that blur the lines between low-beam and high-beam headlights will be described and then analysed in the next chapter.

BMW Adaptive LED headlights

Some BMW vehicles have headlight systems that are aimed at increasing night driving safety and also minimise glare for oncoming traffic, while keeping the light comfortable for the driver. Their "Dynamic Light Spot" is a system that, thanks to a heat radiation sensor, can recognise pedestrians and other living creatures and illuminate them with a targeted beam of light in order to draw the driver's attention to a potential danger.

Another system, called "Glare-free high-beam assistant" makes it possible for drivers to fully take advantage of the high-beam headlights, that are not used often enough for fear of blinding others; this system has a camera sensor that can detect the incoming vehicles' headlight beams from up to 1000 meters, and tail-lights of the vehicles in front up to 500 meters: the assistant then switches from high-beam to low-beam, and then switches back to high-beam once the other drivers are far enough to not be blinded by glare. This system can also measure the ambient light, and, if sufficient, it can switch to low-beam.

An evolution of this system also exists, but it does not switch from high-beam to low-beam: instead, it can detect the position of other vehicles, a mobile glare mask is then applied in order to stop the light shining into other vehicles, while the driver can fully benefit from the high-beam illumination. With this system, the driving comfort also increases: the driver will not have to switch between high and low-beam manually every time a car is close, while also having increased visual range, making night driving less stressful and safer. (*BMW innovations in vehicle lights. 'Dynamic Light Spot' for actively illuminating persons, the 'Glare-free high beam assistant' and full-LED headlights provide even more safety at night.*, 2011)

Image 17 On the left: Dynamic Light Spot. On the right: Glare-free high-beam assistant. BMW. 2011. (Press.bmwgroup.com)

Mercedes Multibeam LED

The Mercedes Multibeam LED also aims to provide the brightest illumination possible while avoiding glare. This system consists of a camera that can detect incoming vehicles and those directly in front of the car, which in turn controls the high-beam LED module which is a matrix light source of 24 individual LEDs. These LEDs are individually controlled and can be dimmed in 255 steps; this headlight can detect the driving situation and produce different light patterns for different purposes: for example, while turning, the light will be targeted towards the turning direction, or, if driving on a wide road, the beam will become wider in order to illuminate the whole width of the road.

This system also includes a mechanical mask that is activated once an oncoming vehicle is detected, in order to block the light shining onto the opposite vehicle; the headlight can also decrease the beam range in order not to dazzle drivers directly in front, and it will keep decreasing, or increasing, the closer or further the other car is.

Additionally, this system also includes a low-beam module, which consists of four LEDs and three low-beam reflectors, which create a homogeneous beam in front of the car. Furthermore, the headlamp also functions as a long-range light on highways and as an enhanced fog light. While most cars have swivelling lights, meaning the headlamps slightly turn when the steering wheel is turned, the Mercedes Multibeam LED headlamp takes it a step further: thanks to advanced sensors, the headlamps can swivel even before the steering wheel has been turned, and will then swivel back into the default position in order to illuminate the road ahead and let the driver see any danger before they finish taking the curve. The manufacturer also states that these LED headlights have a colour temperature of 5500 Kelvin, which is closer to daylight (6500 K) than other cars outfitted with Metal-Halide Xenon lights (usual range of 3000 - 4100 K, and 4200 K according to the manufacturer). (*MULTIBEAM LED headlamps: The future of light*, 2014; *Mercedes-Benz MULTIBEAM LED headlamps*, 2021)

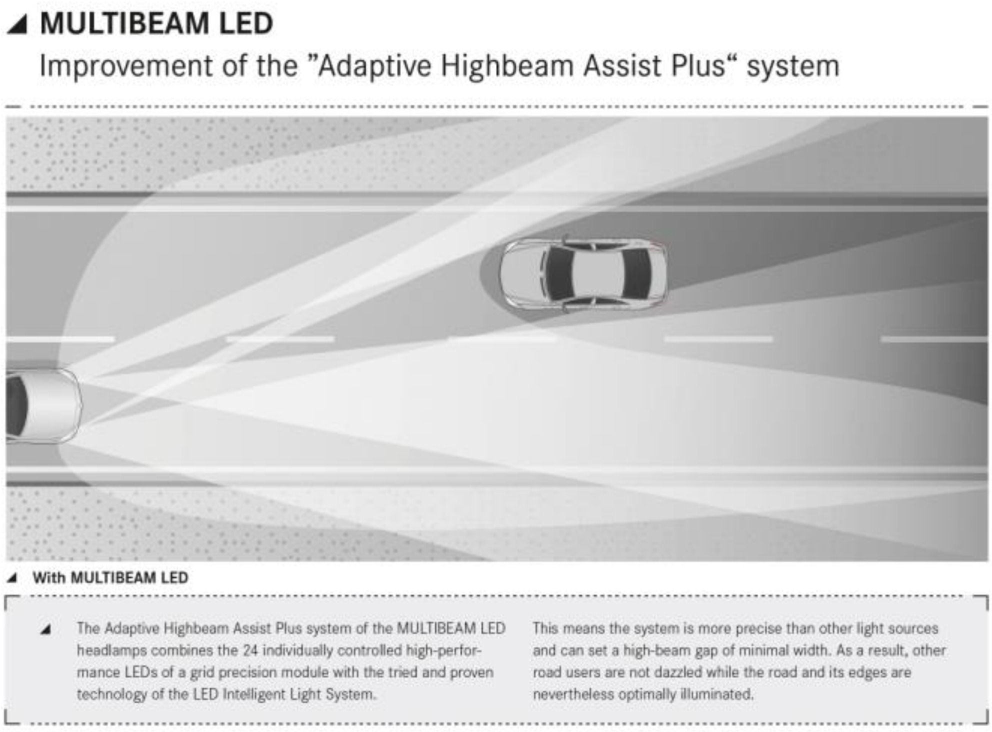

Image 18 Multibeam LED. Mercedes. 2014. (Mercedesblog.com)

Porsche HD Matrix Beam

The Porsche HD Matrix Beam is a system designed to offer extremely homogeneous lighting, while avoiding dazzling the oncoming drivers. This headlight system consists of two chips that include 16.384 micro-LEDs (also called pixels in this case) that can be individually controlled in 1024 steps.

This technology claims to turn night into day, for a distance of up to 600 meters. Since each micro-LED can be controlled individually, the HD Matrix offers great flexibility: thanks to the help of sensors, different patterns can be created, depending on the surroundings. For example, when the high beam is activated and a car is detected, the system will turn off the corresponding pixels in order to mask the light and avoid dazzling the oncoming driver. On top of that, pixels are not always turned on in high-beam mode, as the system only turns on the pixels that are actually needed in any given situation, increasing its energy efficiency.

This technology also has some extra features, such as lane illumination: the vehicle's own lane is brighter, helping the driver detect hazards faster and more easily. This light carpet is either shrunk or widened, depending on the width of the lane and whether the driver is changing lane or not. (*Performance leap in light technology*, 2022)

Image 19 On the left: non-dazzling high beam. On the right: lane illumination. Porsche. 2022. (Newsroom.porsche.com)

AUDI Digital Matrix LED

The AUDI Digital Matrix LED headlight is one of the newest systems on the market, and its principle of function is different from the previous ones: instead of having a chip with many micro-LEDs, this device consists of 1,3 million micromirrors that can shape the beam of light. This technology has been previously used in some projectors and is known as a “Digital Micromirror Device” chip (DMD). Each micromirror in the Matrix LED headlight can be tilted individually at a rate of 5.000 times per second and, depending on the situation, they either redirect the light on the road, or absorb it in order to mask certain areas.

Thanks to night vision sensors, the system can detect pedestrians and highlight them with targeted illumination, helping the driver be aware of pedestrians. On top of that, this system is also glare-free: oncoming vehicles are masked out in order to stop the light from shining onto the other drivers.

Additionally, this system also has other helpful functions, such as lane light, which creates a carpet of light on the driver’s lane, orientation light, which creates darkened areas in front of the vehicle to predict the vehicle’s position in the lane and advanced traffic information, which can project a warning indicator in front of the car to warn the driver of possible accidents on the road. (*Lighting*, 2017; *How Audi’s light digitization is pointing the way toward the future*, 2022)

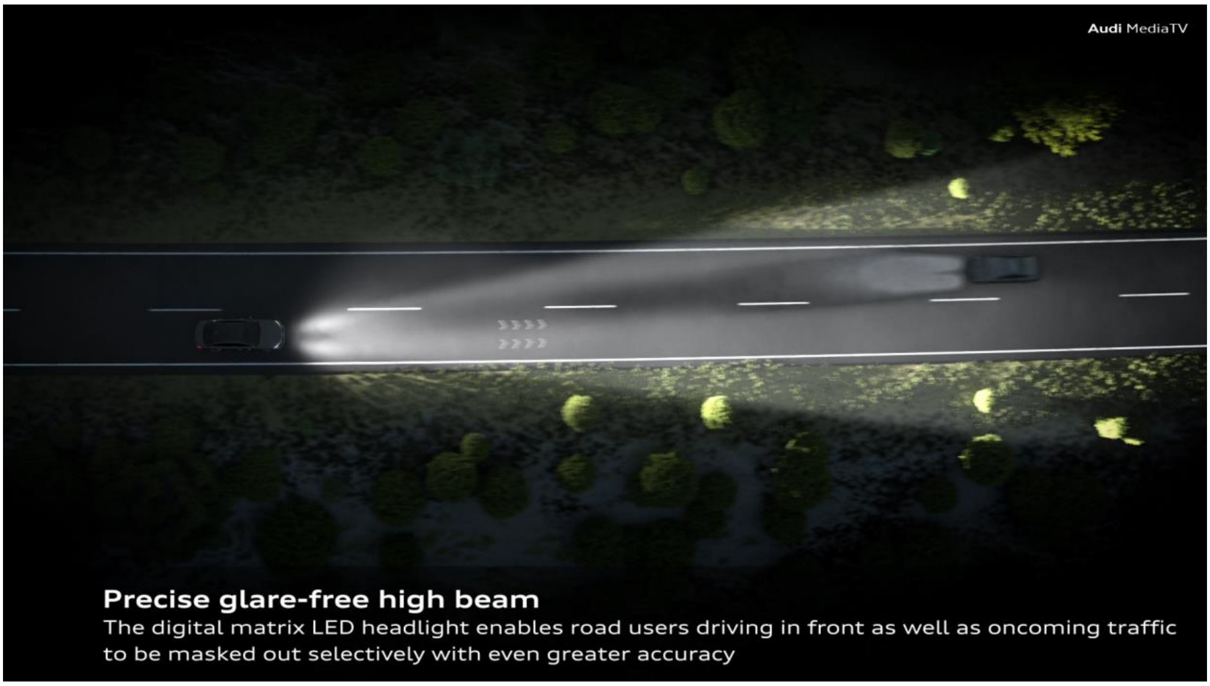

Image 20 Glare-free high beam. AUDI. 2022. (Audi-mediacenter.com)

Carnegie Mellon Smart Headlights prototype

The Illumination and Imagining faculty of the Carnegie Mellon university has developed a highly versatile lighting system that can detect vehicles on the road and mask them out through a spatial light modulator. A spatial light modulator (SLM) is a device that is used to modulate amplitude, phase, or polarization of light waves in space and time; this technology is most commonly used in overhead projectors.

Image 21 Smart headlight, seen from the opposite driver's perspective. Carnegie Mellon. 2015. (Cs.cmu.edu)

Since the light is modulated, and not turned off, dimmed, or blocked, the light throughput is much higher than other technologies that either mechanically mask the light or dim it. This headlight system consists of a camera, that captures images of the road, processor, that analyses the images and calculates the light pattern, and SLM, that modulates the light in order to achieve the desired pattern. This system is highly versatile as it can be programmed to achieve many goals: it can detect other vehicles and mask them out, it can detect and highlight obstacles, it can create lane light and it can detect and mask out individual rain and snow particles in order to increase visibility during poor weather conditions. (*Programmable Automotive Headlights - Anti-Glare*, 2015; *Toward a Smart Automotive Headlight for Seeing Through Rain and Snow*, 2015)

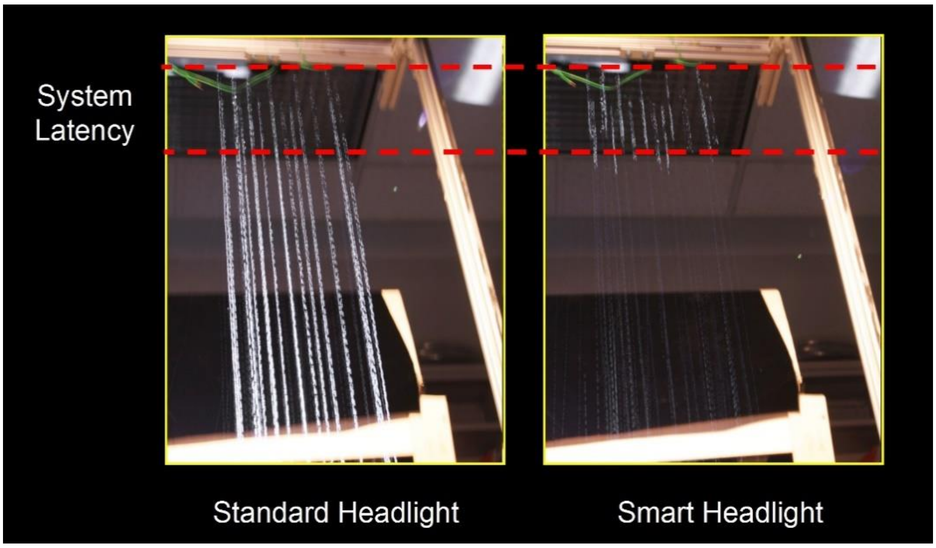

Image 22 Smart Headlight, programmed to mask the light shining onto water particles. Carnegie Mellon. 2015. (Cs.cmu.edu)

4.4 Analysis

In this section, the lighting technologies mentioned in the previous chapter will be discussed and analysed by the author. Each technology will be examined and compared to the others, in order to delineate the strengths and weaknesses, and to discuss what could be improved and done better. The discussion will be purely theoretical, and it will not consider ease of manufacture or prices.

All the technologies described in the previous section have similar working principles and goals, but they are achieved through different methods. These systems all consist of a sensor, that will detect obstacles, dangers, pedestrians, animals and other vehicles and then send this information to a processor, that will then use this information to calculate the appropriate light beam that the advanced headlight will need to produce in order to ensure that dangers are highlighted (in the case of some of these systems) and that other vehicles are masked out, in order to minimise glare for other road users.

However, systems like the Porsche HD Matrix Beam, AUDI Digital Matrix and the Carnegie Mellon smart headlight prototype seem to be more versatile compared to the Mercedes Multibeam and the BMW adaptive headlights, due to the fact that they mask the light through more efficient methods than mechanically blocking the light, which means part of the light throughput is lost. The most energy efficient technology is most likely the Carnegie Mellon headlight system because it modulates the light waves, and according to their findings very little energy is lost in the process compared to the other systems, as the light is not being absorbed or blocked.

Nonetheless, these technologies could probably benefit from having tuneable-white LEDs: most of these headlights produce cooler looking lights compared to their predecessors and, according to some studies (see chapter 4.2.2 Glare), they are associated with higher discomfort glare, especially at night. With the use of light sensors the headlights could switch from cool to warm light depending on the situation and (paired with the anti-glare technology) could further reduce glare.

4.4.1 How glare is approached in other fields: architecture and street-lighting

In order to find good solutions it is also important to observe how glare is treated in other industries, analysing how they minimise glare and potentially applying these solutions to car lighting.

In architecture, glare from the sun and its reflection on windows and other buildings is one important aspect that can influence the final design; it is something that should be avoided as much as possible, especially in buildings where people spend much of their time inside, such as residential and office buildings. Additionally, glare from interior lighting is also an important concern, especially in offices, as a poor lighting situation can create issues for the workers, which range from headaches to decreased productivity.

When it comes to the sun's glare, the most obvious solution is to reduce the light that comes into a building: this can be done from the design phase, by reducing the size of windows (and by placing the opening in a good position, related to the room to illuminate) in orientations where glare is a higher concern (for example, from the south), and / or by using blinds or other types of shading.
Another method is increasing the interior brightness, by using stronger light sources and materials with higher reflectance. However, brighter light sources alone do not necessarily decrease glare: a balanced lighting environment is also important to avoid discomfort glare, as extreme differences in brightness are proven to cause additional discomfort. (Hopkinson, 1972; Kim and Jeong Tai Kim, 2010; Osterhaus, 2016)

In the case of interior lighting, more elements can be controlled, such as the brightness of the light source, the aim, the position, the type of shade, lens, and reflector of the luminaire. In general, a good light distribution is the most important factor when it comes to interior lighting, as glare heavily depends on the light adaptation of the eye, and a higher contrast between the light source and the surrounding luminance can cause discomfort.

The best way to solve glare issues is to have luminaires mounted into the ceiling, away from direct sight; nonetheless, very bright light sources can still cause discomfort glare even when outside of our visual field. This is commonly known as overhead glare and a study from 2013 found that overhead glare can be reduced by reducing the CCT of the glare source: these findings are coinciding with other results from other experiments (shown in Chapter 4.2.2 Glare).
However, the previously mentioned research has been conducted with light sources directly into the field of view, while Zhang's research has been conducted with overhead light sources outside of our visual field, with angles ranging from 55° to 90° in reference to our line of sight. Therefore, reducing the CCT of a light source can decrease the discomfort glare from light sources both inside and outside our field of view. (Zhang *et al.*, 2013)

In streetlighting, creating a glare-free and homogeneous light is a crucial step to ensure safe driving conditions. Streetlights are usually tall poles or hanging lamps that are placed from 3 to 15 meters (in the case of streetlights for vehicle roads) above streets which makes disability glare less likely to happen, due to their higher angle from the plane of vision. The spacing between each pole or hanging lamp relative to the height is also very important, as good uniformity is preferable, and too dark or bright areas should be avoided. (*How Tall are the Streetlights | OEM Supplier | MKLIGHTS*, no date)

However, discomfort glare can still be a problem even when the light sources do not cause disability glare, especially due to excessively bright luminaires and contrast between streetlights and background luminance. Two different experiments conducted with LED lights found that when the background luminance is too low the test participants rated the perception of their discomfort glare as being worse to that of when a fill light was added. (Sweater Hickcox *et al.*, 2012; Space Daily, 2014)

It is recommended to dim the light sources to a more acceptable level (enough for the eye to see whilst not causing discomfort), carefully placing the luminaires in order to create a homogeneous carpet of light and adding fill lights in order to reduce the contrast between the streetlighting and the background. Furthermore, warmer tones of background light are to be preferred (white or yellow), as the blue fill light used in the experiment from 2012 resulted in more discomfort glare, but still an improvement over no background light at all. (Sweater Hickcox *et al.*, 2012)

By following these recommendations both disability and discomfort glare from vehicle headlights can be reduced; however, as mentioned previously, this is only a superficial solution as not all roads can be illuminated.

4.4.2 Applying glare solutions from other fields to the automobile industry

In the previous subchapter different methods of reducing glare from the architectural and streetlighting fields were explained and analysed. In this section these solutions will be analysed in order to determine how they could be applied to the automobile industry, if possible.

In architecture reducing the intensity of the glaring source is possible by blocking or reducing the light that comes inside, if from the sun, or by dimming, changing its position and/or increasing the background luminance, in the case of electrical light. This is not feasible in the automotive industry as blocking the light from other cars is not possible because it would impair the driver's visibility, and the position of the glare sources (other vehicles) are in the field of view of the driver. However, it is possible to take these principles and apply them to the automotive field. For example, increasing the background luminance, with proper use of both streetlighting and vehicle lighting is a good starting point. As mentioned previously, good streetlighting is not possible everywhere, so the final solutions should not hinge too much upon the principle of increasing background luminance to decrease glare.
It is possible to take the idea of blocking light, if not from the source directly, at the destination: researchers from Politehnica University of Timisoara have devised a concept of a type of smart glass that is capable of reducing glare from the sun, by detecting the sun's rays and creating a dark spot that will partially block the light from shining directly into the driver's eyes. (Ungureanu *et al.*, 2020) This technology could also be applied at night to the light that comes from other vehicles, but it could raise concerns about visibility, as blocking the sun will not impair the visibility of the road as the sun is generally much higher than the road, but blocking other car's headlights would most likely impair the visibility of the road.

In streetlighting it is possible to reduce glare by creating a homogeneous lighting situation with the addition of fill light, preferably on the warmer end of the white light spectrum, and by placing the sources far above the road in order for them to be outside of the driver's field of view, and too far to create glare when they are inside the field of view. Dimming the lights is also another solution, which is also done with the classic low beam headlights of cars, but they often do not provide enough illumination. Again, these methods do not work well in the case of headlights, but what can be learned from these solutions is that discomfort glare can be reduced by using neutral white or warm CCTs, while avoiding colder ones.

4.5 Solutions

Headlight requirements have been, until more recent times, partially paradoxical: an intense and well distributed light beam is needed for the driver to properly see the road at night, while at the same time avoiding glare onto other road users; therefore, it was necessary to split the headlight system in two, having a lower intensity beam to use while other road users are present in the vicinity, and a high intensity beam, aimed higher, in order to illuminate the road at greater distances, provided that nobody else was in the vicinity. Due to that, many road users avoid using high-beams, even when they should, in fear of blinding other drivers, at the expense of good vision at night. Additionally, at high speeds many low-beam headlights may not provide adequate lighting, meaning that accidents are more likely to happen. (*Outdated headlights put drivers and pedestrians at risk*, 2017)

Car manufacturers have been juggling with these requirements for decades, either creating relatively glare-free lighting that was not illuminating the roads properly, or by creating really intense headlight system that could greatly illuminate the road, but at the expense of other drivers.

These two main problems, poor performance and glare, are symptoms of either too low or too high luminous intensity, and the headlamp's alignment angle. With the advent of new technologies, such as sensors, cameras and extremely fast processors, driving has become much safer, however, these technologies are rarely applied to headlights, and are currently present only on the most expensive vehicles. As stated in the previous chapter, all these technologies work based on similar principles: by providing the highest possible luminous intensity and by having the best possible light pattern at any given situation, while simultaneously blocking the beam from shining into other road users. Of course, this would have not been possible without progress in digital and computing technologies, as these technologies rely heavily on sensors and fast image processing.

However, one aspect these advanced headlight technologies lack is the different effects that various colour temperatures have on the human eye. Many car manufacturers claim that now their lights are closer to daylight than ever, and while that is a great feature to have, according to the previously discussed studies, light sources with a higher colour temperature may cause more discomfort glare. Therefore, in the author's opinion, it is important to include white-tuneable light sources in these new anti-glare headlights, in order to further reduce discomfort glare.

There are also other arguments to this solution, which are more human-centric: the colder ambient light created by these headlights may tire the eyes faster than warmer light, which will increase the overall discomfort while driving. It is important to remove any potential stressful events from driving, in order to increase safety. However, colder light may increase a driver's vigilance and perception, therefore the argument of warm light versus cold light for night driving may create grounds for further research and testing.

Therefore, based on the findings in this paper, the best headlight system should be an automatic low and high beam system and should achieve the following principles:

- Illuminating the road farther, depending on the speed of the vehicle, giving the driver ample reaction time in case of dangerous obstacles.
- Including an anti-glare system, in order to combat the extended beam range, providing good illumination while at the same time not blinding other drivers or creating excessive discomfort.
- Communicating through light eventual obstacles, for example by highlighting objects, animals, and pedestrians on the street with a brighter beam of light, or, if possible, with a beam of light of a different colour temperature. Furthermore, this beam of light should be kept relatively low, in order to avoid causing glare to pedestrians and animals, which, in the case of animals, may scare and confuse them creating an even more dangerous situation.

- Providing good ambient lighting, by detecting the situation of the surroundings, and choosing the best colour temperature and beam pattern for any given situation.
- Including a self-levelling device in order to minimise usage-related headlight misalignment.
- Including a self-cleaning device in order to eliminate dust and dirt that may cause either poor performance or glare, depending on the stray light.
- Including a dynamic headlight levelling device (dHLS) in order to combat weight and suspension-related changes in the vehicle's pitch, which can lead to a poorer beam range or glare for other road users.

Other optional features, not related to headlights directly, could be smart-glass windshields that are able to partially block incoming lights from other cars in order to avoid causing glare to the driver; however, there has been no research about the possible downsides of this technology, therefore this aspect should be kept into consideration for further study.

5. DISCUSSION

As discussed in the previous chapters, there are already many technologies that provide solutions to the most common headlights problems. However, since they are only present on high-profile cars, the benefits of these headlights are extremely limited, as not everyone can afford such vehicles. Since headlights affect other road users, it is necessary that these solutions be implemented in other vehicles too and, if possible, older vehicles be refurbished with these newer headlights, in order for these issues to be truly eliminated permanently. Only a small percentage of cars have headlights that are considered adequate: in order to truly ensure safety on the roads for everyone these technologies must be applied to the majority of vehicles, otherwise they are only luxury elements that do not really improve driving conditions.

The existing state of the art technologies for headlights are a step in the right direction as they solve many of the problems that were common and seemingly unsolvable with the classic approach of using either the low-beam or the high-beam, even in the presence of other auxiliary headlamps. Nonetheless, there is always a possibility of improvement, both from a theoretical standpoint and a practical one. These new technologies may benefit greatly from complementing their shortcomings by taking inspiration from other similar technologies; for example, the AUDI Digital Matrix can vastly benefit from introducing a weather-based technology like the Carnegie Mellon smart headlight prototype, in order to block the light from shining not only onto other road users but also onto the individual rain or snow particles, further increasing the safety and comfort of driving at night during bad weather.

The challenges of implementing these technologies are many and require multi-disciplinary efforts. These technologies require a team of engineers, programmers, lighting designers, lawyers, and researchers in order to meet all the criteria of the perfect headlight. Since these technologically advanced headlight systems are still in their infancy, there are no global standards to streamline the production and manufacturing process yet, meaning that they will be out of the average person’s range for few more years, but hopefully less. Vehicles are also objects that are not often changed, such as phones or computers, therefore progress comes at a slower pace, despite the theories and prototypes behind such technologies being much older.

The principles proposed in “Chapter 4.5 Solutions” are meant to provide a theoretical framework that can be used as a basis for future technologies. Since this particular topic in this field is so complex, these theories should be validated with real-life experiments and research. Other challenges, such as fitting all the “extra” technologies (such as self-cleaning, self-levelling, etc.) may also arise during the prototyping phase; however, thanks to LED and Laser light sources being much smaller than their classic counterparts it may be easier to fit all these components in the headlights without significantly increasing their size.

6. CONCLUSION

There is a push in the automotive industry to improve headlights, thanks to organisations such as the IIHS and the UNECE, and many automobile companies are developing better technologies. The glare issue is now being approached in a different way, thanks to the progress in the computing and lighting industries: rather than producing only two different beams of light (low and high-beam), now many vehicles have a different range of beams they can produce, based on the surrounding environment and situation.

While some of the most advanced technologies are present only in the top-tier vehicles, simpler versions could be designed and fitted to cheaper vehicles too. The first and most important step would be to include basic anti-glare systems in any and all vehicles; with time, when this technology exits its infancy state, more complex features can be added, following into the footsteps of the luxury vehicles.

Furthermore, providing high-quality high-range glare-free illumination for every vehicle is something that will benefit every road user, increasing their safety and comfort. The night-time driving accidents would hit an all-time low, potentially saving tens of thousands of lives every year.

In conclusion, this paper provides demonstrations on how future headlights could function and what aspects they should consist of. The solutions are based on existing real-life technologies, which are currently only present in luxury vehicles, and builds upon their principles by adding elements that further improve these systems.

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8. APPENDIX

8.1 Perception of Car Headlights / Headlamps (Survey)

As a driver, at **night**:

(LEAVE BLANK IF NOT A DRIVER)

As a driver, at night, what is your perception of the brightness of most cars' front headlights?

	0	1	2	3	4	5	6	7	8	9	10	
Not bright	○	○	○	○	○	○	○	○	○	○	○	Too bright

As a driver, at night, how often do you get dazzled (temporarily blinded) by low beam headlights?

	0	1	2	3	4	5	6	7	8	9	10	
Never	○	○	○	○	○	○	○	○	○	○	○	Always

As a driver, at night, how often do you get dazzled (temporarily blinded) by high beam headlights?

	0	1	2	3	4	5	6	7	8	9	10	
Never	○	○	○	○	○	○	○	○	○	○	○	Always

As a pedestrian, at **night**:

As a pedestrian, at night, what is your perception of the brightness of most cars' front headlights?

	0	1	2	3	4	5	6	7	8	9	10	
Not bright	○	○	○	○	○	○	○	○	○	○	○	Too bright

As a pedestrian, at night, how often do you get dazzled (temporarily blinded) by low beam headlights?

	0	1	2	3	4	5	6	7	8	9	10	
Never	○	○	○	○	○	○	○	○	○	○	○	Always

As a pedestrian, at night, how often do you get dazzled (temporarily blinded) by high beam headlights?

	0	1	2	3	4	5	6	7	8	9	10	
Never	○	○	○	○	○	○	○	○	○	○	○	Always

In general (both when driving and not):

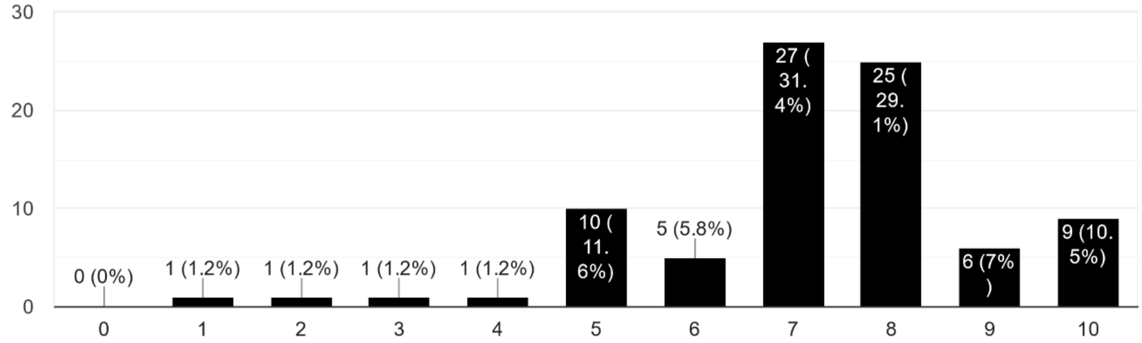
Do headlights with blue-ish lights feel, generally, brighter compared to those with yellow-ish lights?

- ◯ No, they are less bright
- ◯ They are the same brightness
- ◯ Yes, they are brighter

8.1.1 Survey results

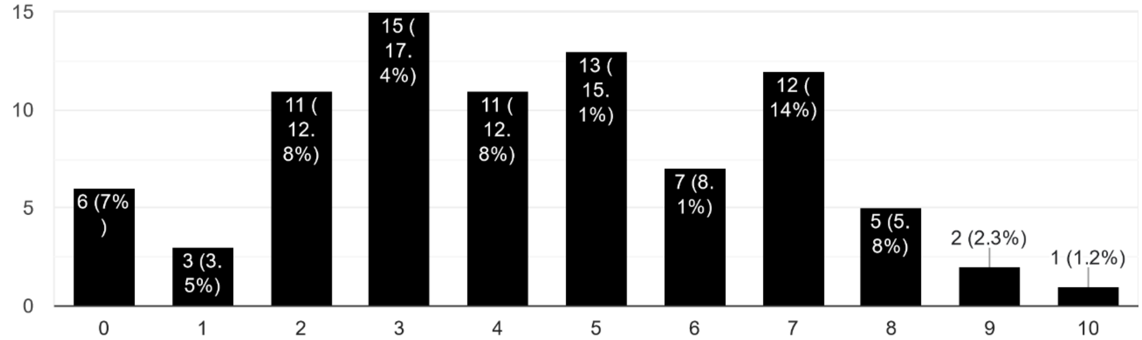
As a driver, at night, what is your perception of the brightness of most cars' front headlights?

86 responses



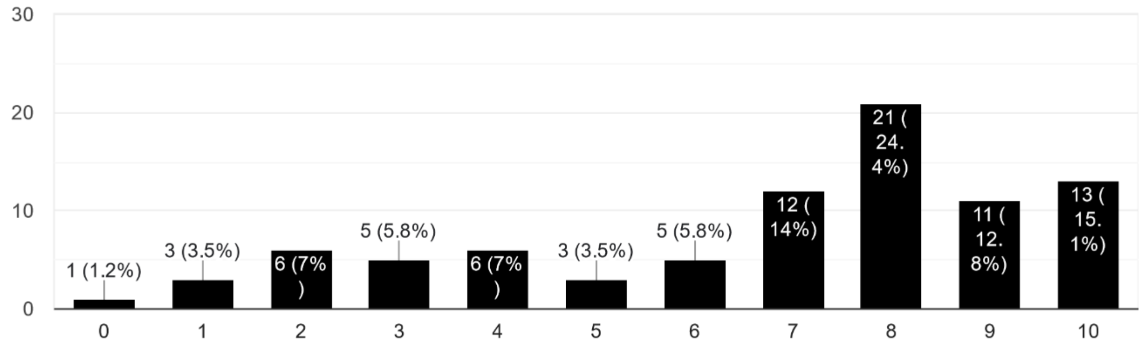
As a driver, at night, how often do you get dazzled (temporarily blinded) by low beam headlights?

86 responses

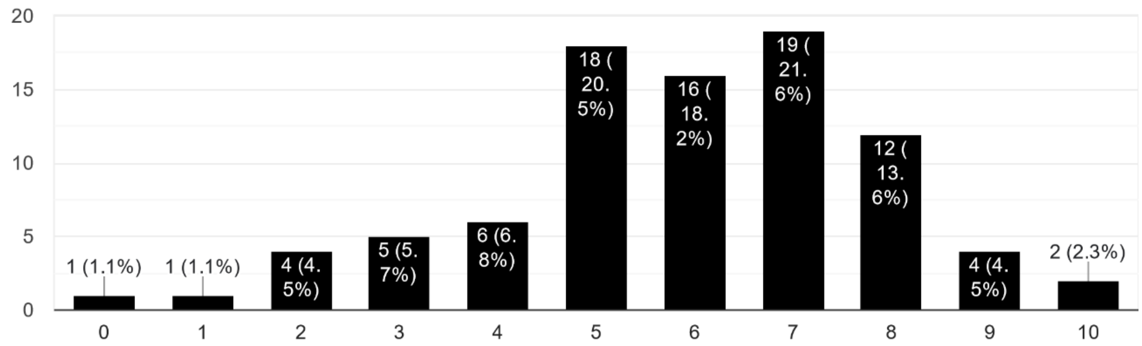


As a driver, at night, how often do you get dazzled (temporarily blinded) by high beam headlights?

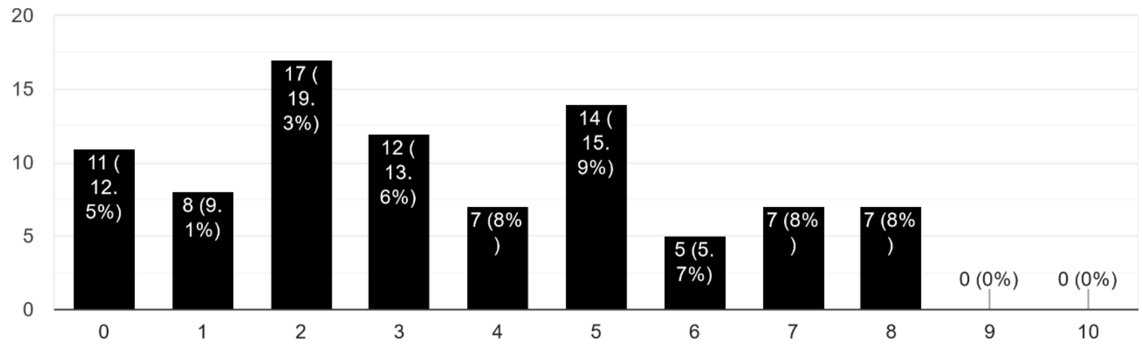
86 responses



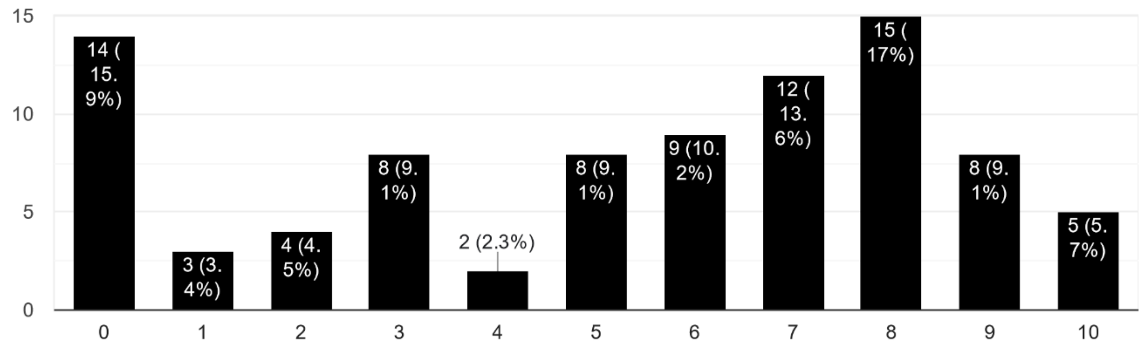
As a pedestrian, at night, what is your perception of the brightness of most cars' front headlights?
88 responses



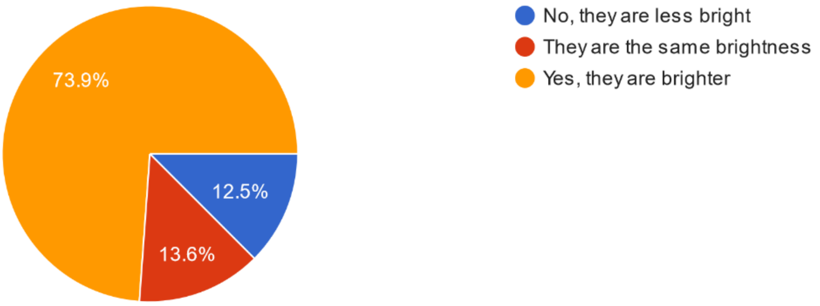
As a pedestrian, at night, how often do you get dazzled (temporarily blinded) by low beam headlights?
88 responses



As a pedestrian, at night, how often do you get dazzled (temporarily blinded) by high beam headlights?
88 responses



Do headlights with blue-ish lights feel, generally, brighter compared to those with yellow-ish lights?
88 responses



8.2 Email correspondence with car manufacturers

Dear -,

My name is Radu and I am a Lighting Design Master's student at Aalborg University Copenhagen. I am currently writing my master's thesis about car headlights titled "Automobile headlights: common problems and possible solutions" and it would be of great help if you could answer some questions I have about the lighting technology you use in your cars. Please note that I am not collaborating with any company in the automobile industry: this research is personal and purely for academic purposes. If there is anything that should not be disclosed in your email reply please let me know, as I can mark my research as confidential.

First of all, is there any more in-depth documentation about the lighting technology you use that I can access?

What are the specifications of the light source(s) of the Adaptive LED? What is the CCT (is it tuneable, does it change depending on the environment?), CRI, Output and Light Output Ratio?

According to my research, a lot of car drivers have problems with glare, does this new technology significantly reduce glare for other drivers? Any external or internal research about glare that was used for this design I can access?

The Adaptive LED seems to have a colder, blue-ish hue, that is usually considered less easy on the eyes than warmer, more yellow toned lights, especially at night. Is this something that has been considered during the design phase? If so, does this colder light have any advantages compared to warmer lights? Or is it an aesthetic choice? Is it feasible to have white tuneable lights that, depending on the time of the day, can change from cool to warm (principle of Human Centric Lighting)?

Many cars have problems with the headlight alignment after many years of use, does the Adaptive LED mitigate this issue? Or do they still need periodic adjustments by a mechanic?

Thank you very much for your time.

Best,

Radu

8.2.1 Example of questions

Sent to AUDI, Porsche, Mercedes, BMW

First of all, is there any more in-depth documentation about the lighting technology you use that I can access?

What are the specifications of the light source(s) in the Digital Matrix LED? What is the CCT (is it tuneable, does it change depending on the environment?), CRI, Output and Light Output Ratio?

According to my research, a lot of car drivers have problems with glare, does this new technology significantly reduce glare for other drivers? Any external or internal research about glare that was used for this design I can access?

The Digital Matrix LED seems to have a colder, blue-ish hue, that is usually considered less easy on the eyes than warmer, more yellow toned lights, especially at night. Is this something that has been considered during the design phase? If so, does this colder light have any advantages compared to warmer lights? Or is it an aesthetic choice? Is it feasible to have white tuneable lights that, depending on the time of the day, can change from cool to warm (principle of Human Centric Lighting)?

Many cars have problems with the headlight alignment after many years of use, since the Digital Matrix LED is using automated mirrors to project the light and create beams, is this issue solved? Or do they still need periodic adjustments by a mechanic?

Reply from Porsche:

Dear Radu,

thanks very much for your interest in Porsche and your request for information about the new headlights. Due to the large number of such requests, we are unfortunately unable to support such requests, unless the respective master thesis is done in a direct working connection to Porsche, e. g. as a Porsche works student or Porsche intern. Please check out our various information sources online, such as our Newsroom (newsroom.porsche.com) and the press database (https://presse.porsche.de). Sorry I have no better news on this topic, but I am sure you will find many answers in material that is already published.

Thanks again for your understanding and best of luck for your studies!

https://media.porsche.com/mediakit/hd-matrix-workshop

https://newsroom.porsche.com/en/2022/innovation/porsche-led-main-headlights-with-hd-matrix-beam-light-technology-30770.html

Best regards

Hermann-Josef Stappen

Dr. Ing. h.c. F. Porsche AG

Communications, Sustainability and Politics
Corporate and Product Communications

Spokesperson Research and Development, Technology Communications