

## Article

# High-Resolution Pixel LED Headlamps: Functional Requirement Analysis and Research Progress

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**Abstract:** High-resolution pixel LED headlamps are lighting devices that can produce high-resolution light distribution to adapt to road and traffic conditions, intelligently illuminate traffic areas, and assist drivers. Due to the complexity of roads and traffic conditions, the functional diversity of high-resolution pixel LEDs headlamps and traffic safety has come into question and is the subject of in-depth research conducted by car manufacturers and regulators. We summarize the current possible functions of high-resolution pixel LED headlamps and analyze ways in which they could be improved. This paper also discusses the prospect of new technologies in the future.

**Keywords:** high-resolution headlamps; traffic safety; micro LED; matrix lights



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## 1. Introduction

In the field of autonomous driving, various sensors are combined with car headlamps to reduce the occurrence of traffic accidents. In addition to the quasi-static low beam function, car headlamps can also provide the driver with various road information [1]. Such a system is conducive to reducing the occurrence of traffic accidents while being restricted by traffic laws [2].

High-resolution LED pixel headlamps are new types of headlamps that use LED arrays for pixelated lighting. By acquiring information from various sensors [3], they can intelligently control the brightness of the corresponding LEDs to achieve intelligent distribution of light effect. Compared with the existing driver's dashboard and head-up display (HUD), high-resolution LED pixel headlamps can project various information of the vehicle onto the car's forward street at night, which has a warning effect, and the driver does not need to adjust the latest information of vehicles that can be obtained by sight, laying the foundation for the future development of unmanned driving.

Due to the complexity of the external environment and the road conditions, high-resolution LED pixel headlamps are also constantly developing. The main idea is to provide the best driver and road participants by changing the corresponding light distribution according to the external environmental information regarding the traffic conditions.

The variability of the driving environment requires high resolution and stability. At the same time, it is restricted by corresponding traffic laws. In order to provide the best driving environment and reduce the occurrence of traffic accidents, various technologies can be used, and each form of technology has its own advantages and limitations. The article first analyzes the overall performance requirements of high-resolution LED pixel headlamps, then introduces the current technology to achieve high-resolution LED pixel headlamps in detail, and finally discusses prospects for its future development.

## 2. Functional Requirement Analysis

Headlamps with high-resolution beam technology provide highly flexible light distribution advantages in the fields of high beams and adaptive drive beams (ADB). The current high-resolution LED pixel headlamps are not limited to pure far and low beam functions. Through segmented lighting of the traffic area, the brightness of each segment is controlled to realize the intelligent light distribution design, and each controllable area is the resolution of the headlight. The most mentioned in the literature are the distribution of pixel requirements for high-resolution headlamps, the diversity of the headlight system, the stability of projection, the rationality of the law, the fusion with sensors, and the customization.

### 2.1. Pixel Requirements for High-Resolution Headlamps

Pixel resolution is the most commonly used indicator. Angular fraction is defined as showing how large the solid angle of a single pixel is [4]. The number of pixels of high-resolution headlamps is the size of the area where the headlamps can be controlled. Reinprecht [5] et al., based on actual road testing and analysis, combined high-resolution headlamps for corner lighting with the function and the radius of curvature of the road, the usage scenarios of vehicles, and common anti-glare objects. Each function corresponding to another requires the resolution to be less than  $0.02^\circ$ . Moisel [6] et al. pointed out that the resolution of high-resolution pixel headlamps not only depends on the number of pixels at the light source side, but that it is also related to the overall structure of the optical system. Based on this, a resolution requirement of  $0.05^\circ$  was produced. Brunne [7] et al. analyzed several lighting functions of high-resolution pixel headlamps and produced a resolution requirement of  $0.03^\circ$ . Based on the analysis of the literature, Marvin [8] et al. produced a resolution requirement of  $0.05^\circ$ .

Pixel resolution is the most basic requirement for car headlamps to project icons, etc. Each headlamp has different functions, and the requirements for pixel lamp resolution are also different, as they are determined by the functions that need to be realized. According to the literature analysis, a resolution of  $0.05^\circ$  is reasonable for most lighting functions.

### 2.2. Variety of Beams for High-Resolution Headlamps

In addition to meeting basic lighting requirements, high-resolution LED pixel headlamps also provide advantages for all lighting functions with their controllable light distribution. Projection is the most common function. With the continuous development of high-resolution headlamps, the patterns projected are also constantly diversified.

Far- and near-road lighting are the most common forms. At present, some basic projections have been developed, such as left- and right-turn arrow indications, pedestrian yielding, danger indications, and brand display. Figure 1a shows the attention bicycle lighting function, which was designed to remind the driver to pay attention to the bicycle ahead and drive carefully. The lighting function is being transformed into new style possibilities and safety functions through high-definition technology functions.

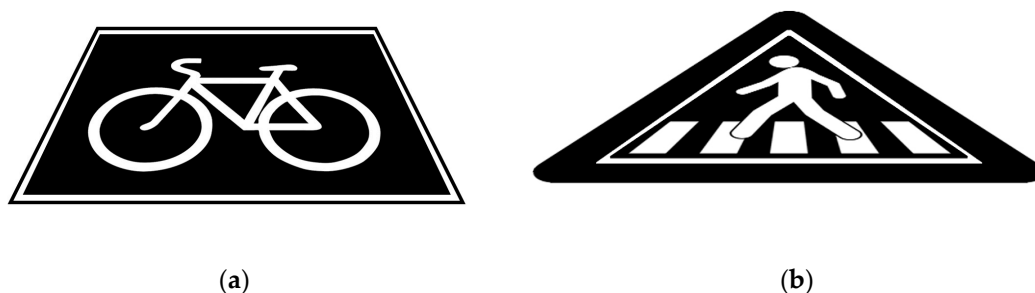


Figure 1. (a) “Attention bicycle” icon. (b) “Attention pedestrian” icon for high-resolution headlamps.

Rosenhahn et al. divided the road planning projections of high-resolution LED pixel headlamps into two groups [9]. The first group is information and warnings for drivers, such as obstacle warnings, speed limit reminders, and real-time navigation information. As shown in Figure 1b, this lighting function can prompt pedestrians on the zebra crossing to go first. The second group is assisted driving, for example, indicating the width of the construction road.

Kleinkes et al. divided the lighting styles of high-resolution LED pixel headlamps into six categories [10]. The first category is welcome and farewell lights, whose purpose is to impress people; the second category is non-glare high beam lights, which are designed to reduce the shadow area around oncoming traffic participants to improve driving safety, as shown in Figure 2a; the third type is the optical lane assist system, which estimates the width of the vehicle and warns other road participants to reduce steering wheel adjustment and reduce driving; the fourth type is dynamic, which aims to enhance the understanding of light during night driving; the fifth type is reasonable light distribution, which aims to adapt to more complicated roads and the driving direction of vehicles; the sixth type is light distribution safety, such as variable lanes for bicycles and safe distance from neighboring cars, which is implemented to improve the safety of other road participants.

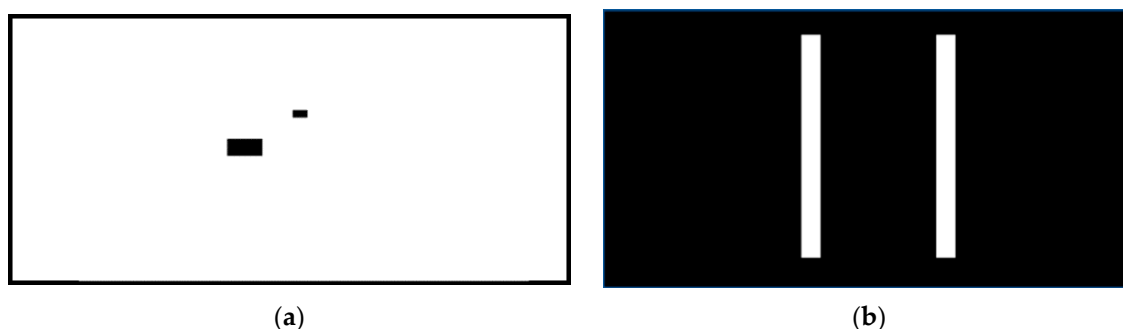


Figure 2. (a) “Meeting car anti-glare” icon. (b) “Road planning construction site” indicator icon.

According to Gut et al., due to the re-planning of road construction at night, the radius of passing small bends causes safety hazards for drivers [11].

Qiao et al. analyzed the driving simulator data of 18 road participants in the construction area and found that the more obvious the notification system is [12], the more it helps to avoid rear-end collisions in the construction area. Smartphone reminders are limited and rely on the most common systems. As such, car headlamps are more helpful in providing drivers with reminders.

Hamm et al. mentioned in their research that, in overtaking or poorly illuminated roads in the construction area [1], when there are huge obstacles on the front road, lane bend and traffic accidents are likely to occur. The lights in the construction area project, that is, two light stripes on the road to warn the driver of the width of the road, improve the safety and the comfort of the driver, as shown in Figure 2b and examined through experiments. About 80% of participating drivers thought it could guide them well. The direction of the high-resolution headlamps projected around the construction site makes it easier for the driver to manipulate the steering wheel [13], and the information projected by the high-resolution LED pixel headlamps on the road shortens the driver’s reaction time to obstacles and the braking response time [14].

Wilks et al. also proposed a similar concept [15]. The light distribution is a kind of curved light, and the high-resolution LED pixel headlamp can specifically adapt to road surface, curvature, road crossing, and branching.

High-resolution LED pixel headlamps can meet the current needs of lighting, warning, and assisting drivers with their controllable pixel distribution. Compared with other similar products, they have the advantages of a shortened reaction time, more concentration, and safe driving.

### 2.3. Stability of High-Resolution Headlamps

High-resolution headlamps require real-time feedback on the information collected by the car. At the same time, the complexity of the traffic road requires the system to be capable of real-time correction and self-checking.

Schmidt proposed that the use of high beam lighting in severe weather such as rain and fog increases the glare more significantly [16]. Therefore, special lighting strategies are required under severe weather conditions. The development of adaptive headlamps can solve this problem, especially on wet and rainy roads, when the forward reflection of wet roads can directly look at oncoming vehicles, and the high-resolution headlight adaptive area can extend from the high-light area to the near field, depending on the width of the passage and the surrounding area of oncoming vehicles. In the tolerable shading area, the vertical opening angle of the light source module requires different high-definition resolution.

Hamm et al. investigated the behavior of vehicles at night under wet or dry road conditions [1]. The Audi Driving Experience Center in Germany used two interoperable test tracks to test the impact of directly reflected light on drivers in wet weather. By rating the low beam, the high beam, and the digital light separately, it was observed that, under humid conditions, due to the influence of reflected light, the low beam and the digital light are satisfactory in the glare level, while the high beam is clearly dazzling. All experiments and test results show that digital light can improve the lighting environment in critical and extreme weather to a satisfactory extent, and digital light does not produce additional glare.

In the research on the use of matrix headlamps in fog by Rosenhahn et al., it was found that the increase in the luminous intensity below the cut-off line of matrix headlamps can improve visibility in foggy conditions [17]. They suggested that high-resolution headlight systems can be used to achieve higher visibility.

Thoma et al. pointed out that, under bad weather conditions, reduced visibility and dazzling caused by rain and snow lead to wrong judgments and cause traffic accidents [18]. The light distribution must be adjusted according to general visibility and the visibility of the light source. Based on the visibility measurement of the target and the subjective scores of the participants, the potential of high-resolution headlamps to improve visibility in fog was confirmed.

Ravier et al. pointed out that ADB can illuminate the area where the low beam fails to reach the light and improve the safety of autonomous driving [19].

Gut et al. elaborated on the importance of high-resolution headlamps for autonomous driving [20]. At night, sensors must be able to detect rain, fog, snow, and street conditions such as wet and frozen roads. Headlamps can support camera detection of objects at night. Providing better night lighting for autonomous driving is one of the most important tasks of new technology digital light technology. This means that light distribution and intensity of the high-resolution LED pixel headlamp system will be precisely controlled according to the needs of the vision sensor. Therefore, high overall stability is necessary, high-resolution headlamps are an important part of lighting, and self-repair is inevitable.

Janke et al. proposed a “self-healing” measure for matrix headlamps [21]. The highly adaptive headlamps compensate for the failure of one or more adjacent LEDs by controlling other LEDs. Studies have shown that, even if there are one to two LEDs that are malfunctioning, the unevenness caused by local dimming can be improved through reasonable light distribution and “self-healing” measures.

Severe weather is one of the main factors of traffic accidents. High-resolution LED pixel headlamps can adjust the light distribution in real time according to general visibility and the visibility of the ambient light to reduce the occurrence of traffic accidents. On the other hand, the controllable light distribution of high-resolution LED pixel headlamps can improve the local dimming caused by local LED damage through reasonable light distribution adjustments, and it can also reduce the cost of replacing car lights.

#### 2.4. Legal Rationality of High-Resolution Headlamps

High-resolution headlamps require real time feedback on the information collected by the car. At the same time, the complexity of the traffic road requires the system to be capable of real time correction and self-checking.

High-resolution headlamps are subject to corresponding regulations. The main purpose of their lighting is to provide drivers and road participants with the best road traffic environment without affecting other road participants.

Symbol projection can improve the safety and the comfort of drivers, but whether the projection has an impact on road participants is also worth studying. Even if the lighting function is well implemented in the design, it should not distract the driver or the pedestrian under any circumstances. For this reason, the realization of lighting functions must follow a user-centric approach. For the sake of safety, this type of lighting function has been simplified and unified [22].

Krief et al. conducted a test of projecting road signs through a car equipped with a digital light processor (DLP) module headlight system and a liquid crystal display (LCD) module [23]. Most participants said that the optical road assist system is useful, but the speed prompt has certain limitations, such as on wet roads. The visibility of the upper projection is poor. As shown in Figure 3a, The deer crossing is considered to be more practical because it is suitable for open roads and is contrary to the permanently installed road signs. The navigation arrow is used to guide the driver along the test track, which may replace the navigation voice, while the text and the complex animation are considered difficult to read and require a long reaction time. The dynamic cyclist safety zone is a projection of a circle, which projects an additional curve in the bicycle area. The test results show that it can attract the attention of the driver and provide a safe driving area for pedestrians. Many people think that dynamic projection is unnecessary, because it easily distracts pedestrians. Research has shown that simple compliance does not cause any safety hazards to road participants, but the current research is only in its infancy, and the main problem at present is to find simple and easy to remember icons.



**Figure 3.** (a) “Attention deer crossing” icon. (b) “Pay attention to the car” icon from the rear side.

Dmitrij et al. studied the possibility of distraction by other drivers through predicted digital micromirror device (DMD) information [24]. The test results show that the projection does not distract road participants, nor will it hinder or annoy any drivers. Hamm’s test shows that high-resolution headlamps are installed on wet roads, and the increased road projection to the low beams does not increase the glare to prevent oncoming traffic.

Azouigui et al. proposed the function of high-resolution headlamps for parking exit indications [25]. They participated in the test for drivers and pedestrians. Compared with reversing lights, the testers believed that the parking lot projection signal that enhanced safety was useful and did not affect other road participants. As shown in Figure 3b, the projection signal can be more easily recognized than the reverse signal, which greatly increases the number of safety behaviors, such as parking and slowing down, especially



for pedestrians who are not sufficiently focused enough or are distracted by their mobile phones.

In order to investigate the safety impact of parking instructions in the parking lot, GTB commissioned ELS to conduct a study in cooperation with the Karlsruhe Institute of Technology. This study showed that high-resolution headlamps transmit information independently of lighting technology to enhance safety [26].

In our general understanding, the projection effect of high-resolution LED pixel headlamps affects other road participants. Some existing studies have shown that simple compliance does not cause any safety hazards to road participants, and it does not distract the attention of other road users, thereby providing drivers with an adequate driving experience. The main problem at present is the identification of simple and easy to remember icons.

### *2.5. Fusion with Sensors for High-Resolution Headlamps*

At present, existing automatic driving environment perception modules install multiple sensors in various parts of the car and do not have integrity. With the increase in the number of sensors, redundant information input about values and methods, and high-resolution LED pixels, the combination of headlamps and commonly used devices represents a future development trend, and it is also a direction currently being discussed by manufacturers and research institutions.

Austerer et al. proposed that, due to the complex road driving of vehicles, when the sensor is driving on rugged mountain roads, there will be a cut-off line to move up and down and increase the computing time [27]. In order to release the full potential of high-resolution lighting, precise alignment and stability of light distribution are essential elements. Through the intelligent sensor fusion algorithm used to obtain a detailed vehicle environment and direction dynamic information, and using high-pixel headlamps to enhance the user experience by accurately guiding light, the duration of scene creation and the shape of high-resolution headlamps can be enhanced, compensated by prediction algorithms and eliminating high-frequency light oscillations caused by road interference.

Cochard et al. proposed that, although more mature technologies such as radar, ultrasound, and camera technologies can be used in various fields of autonomous driving, in order to meet the National Highway Traffic Safety Administration (NHTSA)'s relevant road regulations, in addition to advanced driver assistance system (ADAS) [28], spectral sensing is also particularly important and has good performance in 3D and in long-distance range. Photonics is currently the only technology that can meet the requirements.

Hartmann et al. discussed the challenges and the benefits of integrating digital lighting and sensor modules [29]. The overall goal is to integrate sensors for autonomous driving into the headlight system. Traditional information acquisition is only used to provide freedom for some special applications. The fusion of spatial information sensor data ignoring the optimization of lighting fusion is mainly guided through the perspective of perception rather than deeper recursive guidance with perception functions, ignoring the reliability of the installation location and the feasibility of dealing with bad weather. The author proposes to integrate a single sensor in the headlamps and gradually develop some of the basic capabilities of current vehicles regarding the peripheral photonic system.

As the driving environment becomes increasingly complex, autonomous driving requires an increasing number of sensors, which, together with computing and communication capabilities, are gradually increasing. The combination of high-resolution LED pixel headlamps and sensors can reduce computing time, eliminate light shocks caused by road infections, and save costs, which is a trend in the current research.

### *2.6. Personalized Customization of High-Resolution Headlamps*

The new lighting function and light distribution are derived from the light distribution proposed by the research results of Damasky [30], Huhn [31], and Diem [32].

Diem et al. mentioned in their related research that, in different environments, the line of sight of the human eye differs [32]. On the highway, drivers mainly focus on the distant environment, while in urban areas, drivers mainly focus on the near environment.

Wagner et al. tested the impact of street lighting on the driver's vision through a study [33]. The main research finding is that road lighting is the most basic source of lighting for cars to move forward. Under different circumstances, when the level of headlamps is reduced, subjects can still drive safely in this situation. The tested vehicle is a BMW 3 series equipped with standard LED headlamps. By controlling the duty cycle of each LED (0–255), 16 dimming levels are used to adjust the brightness of the light. The testers conduct tests on different streets, mainly evaluating the low beam irradiation area and the high beam irradiation area. The results show that the corresponding light adjustment can be carried out according to the corresponding street lighting situation and road position, and it does not affect safe driving within a controllable time.

According to current traffic data, Kobbert et al. evaluated the impact of various headlight parameters on the driver through on-site measurements, analyzed the detection distance under different lighting conditions, and obtained the recommended luminous intensity under a specific safe driving distance [34]. There are obvious differences in different streets. For the difference, in response to the above problems, based on the concept of environmental protection, a segmented lighting method is proposed. The driver's line of sight behavior, the speed of the traffic area, and the street lights are established in a database, and light distribution is calculated according to the database.

Neitzke et al. suggest that each headlamp system should have a dedicated parameter setting system [35], and that the behavior of the entire system should be adjusted to adapt to specific customer needs. For example, when a car goes uphill, pixels can be defined according to the angle of the slope. Preferences should be determined and adjusted to independent “raw values” from sensors, and all car movements should be analyzed, thereby allowing for customers to be provided with a proprietary database.

The development of machine learning and big data has made travel more intelligent. Car headlamps are equipped with a special data system, and personalized lighting according to personal preferences is also a current trends. Light distribution is a new concept with important trends expected in the future

### 3. Research Progress of High-Resolution Headlamps

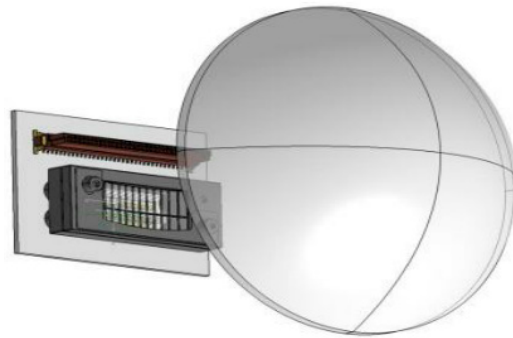
In view of the above functions, manufacturers and research institutes are currently studying methods to meet various needs.

In the field of modern automotive lighting, the development of LED drives the innovation and the development of automotive lamps. Spatial light modulators (SLM, DLP, LCD, MEMS scanners) are widely used in high-pixel automotive headlamps. The DMD technology developed by Texas Instruments (TI) can achieve the highest resolution ( $0.013^\circ/\text{px}$ ) currently on the market [36], using the rotation of 1.3 million mirrors to achieve light distribution with a short switching time and fast response time. On the other hand, the development of microLED and miniLED has slowly changed the pattern of existing high-resolution pixel headlamps. The latest high-resolution technology is pixelized LED arrays. The spatial light modulator system absorbs various parts of the light to adjust light distribution, and high-resolution LED pixel headlamps only generate light where needed, thus the system efficiency of high-resolution LED pixel headlamps, which are composed of thousands of LED pixels in each LED array composition, is high.

#### 3.1. Structure and Performance of Existing High-Resolution Headlamps

Gordon showed a  $3 \times 11$  LED array light distribution module [37]. As shown in Figure 4, the LED adopts Philips' small ceramic LED, the size is  $2.3 \times 1.9$  mm, the driving voltage is 1.5 A, and the highest it can achieve is 265 lumen. The LEDs are collimated by a near-mode collimator and then distributed through a projection lens, which can achieve an angular resolution of  $1.5^\circ$ , and each LED can be individually controlled. The

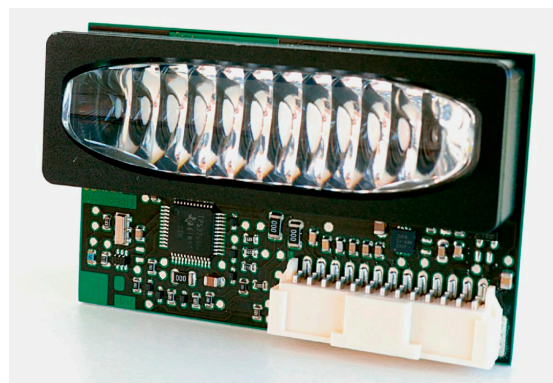
distance between the light source and the optical system determines the resolution of the system and also determines the brightness of the center point. Due to the Lambertian luminescence characteristics of LEDs, a short focus system is generally used. The problem of dazzling oncoming vehicles can be avoided, and a  $15^\circ$  cut-off line of light and dark is generated through high contrast, which realizes far and near light illumination and anti-dazzle functions of the car lights.



**Figure 4.** LED matrix using pre-optics projection lens.

Audi's matrix headlamps [38] consist of 25 LEDs; each LED chip generates a main beam segment in the form of a vertical strip. A total of 25 LEDs form 25 light segments, each of which is independent and affects the others. Cars along the road can produce 100–150 lx luminous flux, thus the driver can clearly see the road with high beams. The matrix beam design allows each light segment to work independently as a camera or a sensor. When an oncoming car is detected, the anti-glare effect can be achieved by turning off the LED of the light segment. The advantage of this technology is that the area dimming is not realized by mechanical blocking or rotation, which facilitates more energy-saving and reduces the volume. However, due to the limitation of LED volume, there is still the problem of insufficient flexibility.

Osram developed the first-generation LED matrix system "Smatrix" [39]. The light source is the Osram Black Flat from Osram Opto Semiconductors with its low thermal resistance and high output even under extreme conditions, as shown in Figure 5. The biggest advantage of this module is the long-life silicone optics used as the collimation system of the LED system. The entire optical system is relatively small and compact, with good heat resistance and freedom, and its degree is high. The LED adjusts the input current on the voltage regulator through PWM, and each LED can be independently controlled. Compared with matrix light, it not only has an anti-glare function but also can be used for static low beam. There are  $3 \times 12$  LED lights, which can adapt to the needs of different types of vehicles.

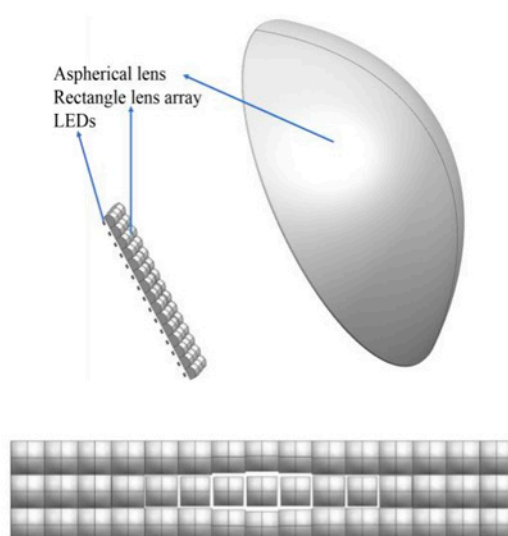


**Figure 5.** The dimensions of the Smatrix module.



The luxeon chip developed by Lumides solves the problem of chip size. The matrix HD84 headlight module launched by HELLA used this chip to produce HELLA's first high-definition digital headlight [40]. The size of the chip is only  $0.5 \text{ mm}^2$ ; it has a high voltage low current and good heat dissipation performance, and its single luminous flux can reach 150 lm under 750 ma current. In addition, the light-emitting area accounts for more than 95% of the overall size of the chip. This model uses 84 independent silicon lenses to collimate the LEDs, and then the rays after collimating through a preset lens are projected by area division to achieve the illumination of 84 areas at 25 m. Compared with the traditional LED headlights, the flux is increased by 2.5 times to 84 light segments. The 84 light segments are independent of each other, and the brightness of each LED can be controlled by the corresponding control system. When the camera or the sensor detects an oncoming vehicle, the system can selectively turn off or reduce the brightness of the corresponding LED to reduce driver dazzling. A total of seven different low beam lighting modes are available, namely, town lighting mode, country lighting mode, low speed/static fill light mode, dynamic curve lighting mode, economic lighting mode, parking lighting mode, and severe weather lighting mode. These seven low-beam lighting modes have their own characteristics that adapt to different lighting functions. When the car is turning, the dipped beam can be illuminated by the LED flowing water as a mobile lighting to realize the function of cornering assistance.

Chen designed a matrix car headlamp module with a matrix lens array, as shown in Figure 6, which can generate independent and non-overlapping rectangular light spots as needed [41]. There are a total of 45 luxeon chips developed by Lumides. Each LED chip corresponds to a rectangular lens. The output current of each LED is 500 MA, the voltage is 3.2 V, the light-emitting angle is  $128^\circ$ , and it can produce 150 lm luminous flux. It uses Lucidshape 2.0 software to realize optical simulation analysis. The secondary light modulation of the spherical lens achieves the required light distribution. The lenses of the rectangular lens array are not strictly symmetrical, which can avoid overlapping rectangular spots. The simulated horizontal beam angle is greater than  $30^\circ$ , the vertical beam angle is greater than  $8^\circ$ , the overall optical efficiency is 30.93%, and the luminous flux at 25 m is 1670 lm. Turning off some LEDs can realize the anti-glare function of the opposite driver.

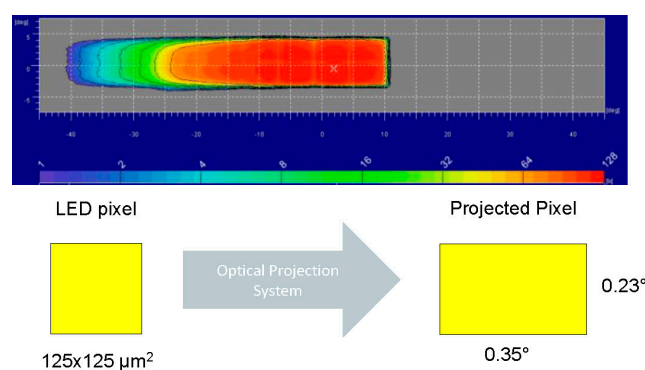


**Figure 6.** Chen's matrix headlamps schematic diagram of optical system array.

At present, the matrix concept is the most commonly used technology for ADB automotive headlamps. However, due to the size of the LED and the limitation of its condenser lens, even if it is less than 100 pixels, it still needs a large area to be produced, and it is difficult to achieve a high number of pixels. Compared with matrix LEDs, pix

LEDs represent a relatively innovative solution that uses the intelligent ADB system as a light source. Pix LEDs do not need to consider the asymmetric distribution of individual pixels, and the area is small, the distance between each LED is short, the minimum is about  $20\text{ }\mu\text{m}$ , and the contrast is high.

At present, there is a relatively mature solution, namely, Osram's EVIYOS chip [42,43], which can realize a  $0.25^\circ/\text{px}$  system. Multiple pixel flip-chip LED chip arrays are directly mounted to the active driver, and 1021 pixels are addressed at a single speed through the serial data bus. The LED flip-chip is mounted on the silicon matrix driver chip with very small gaps and relatively uniform light distribution. In order to obtain a wider light distribution at 25 m, the optical system uses complex asymmetric projections for the secondary distribution of light and uses anamorphic lenses to correct color and distribution. As shown in Figure 7, the pixels between the LEDs are  $125\text{ }\mu\text{m}$ , with a total of  $32 \times 32$  pixels, and the total luminous flux can reach 3072 lm [44]. The control electronics of a single pixel are integrated on the chip to achieve precise control of each pixel with small size, low optical complexity, and high energy efficiency. The actual simulation efficiency of the headlamp prototype based on the EVIYOS chip exceeds 50%. The simulation effect is shown in the figure below. The horizontal angle of the left lamp is  $-40^\circ$ , the vertical angle is  $8^\circ$ , and the optical system resolution of the light distribution center is horizontal. The horizontal direction is  $0.35^\circ$ , and the vertical direction is  $0.23^\circ$ .



**Figure 7.** Simulated view of headlamp light distribution with Osram's EVIYOS chip.

Trommer et al. developed a prototype with a total of 4096 pixels with four EVIYOS chips [45]. Two front lights produce asymmetric light distribution. The horizontal angle of the left front light is  $-28^\circ$ – $5^\circ$ , the angle in the vertical direction is  $-2^\circ$ – $6^\circ$ , the resolution of each pixel is  $0.25^\circ$ , the maximum illuminance value at 25 m is 110 lx, and the total luminous flux is 5700 lm.

Since the EVIYOS chip has an aspect ratio of 1:1, in most resolutions at present, in order to cover the recommended  $40^\circ$ , the left and the right headlamps can be superimposed asymmetrically [46], thus the  $10^\circ$  vertical illumination range VFOV is determined by an aspect ratio of light distribution of at least 4:1. Moellers et al. proposed the concept of deforming projection to reduce the final adjustment work and increase the illuminance at the same time [47–49].

Roth et al. tested the feasibility of anamorphic lenses through three modules, two of which are rotationally symmetrically applied to most of the light emission; the third lens achieves a 2:1 ratio, and the resolution of each pixel is  $0.6^\circ$  [50]. With a luminous flux of 4423 lm and a maximum illuminance of 144 lx at 25 m, the experiment shows that the horizontal illumination ranges of the left and the right headlamps are  $-20^\circ$  to  $10^\circ$  and  $-10^\circ$  to  $20^\circ$ , respectively, and the two headlamps are superimposed asymmetrically. When the HFOV's illuminance is increased by four times, the horizontal and the vertical pixels are also increased, and the desired light distribution can be achieved by projecting the field of view with a half-pixel offset in horizontal and vertical directions.

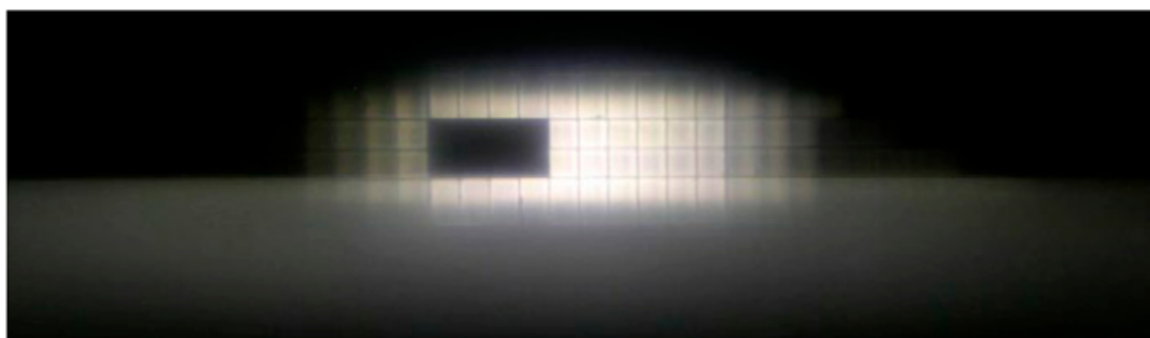
CREE exhibited an LED car headlight with 4000 independently controlled pixels in cooperation with Valeo at the 2019 Consumer Electronics Show but did not elaborate on related products [51].

Werner announced the launch of Osram's second-generation EVIYOS smart car headlamps [52]. Compared with the first-generation EVIYOS, the second-generation EVIYOS has 25,600 independently controllable pixels, and the entire area is only about 40 mm.

Due to the size limitation of the LED chip, the existing matrix headlights cannot achieve high pixels, and it is difficult to achieve the requirement of a resolution less than 0.05 degrees, therefore making it impossible to implement the projection function. Only some simple functions such as anti-glare and corner assist can be realized. Pix LEDs are a relatively innovative solution that uses the intelligent ADB system as a light source. However, due to the limitations of current technology and other factors, it is currently difficult to achieve its mass production.

### 3.2. Existing Beam Diversity of High-Resolution Headlamps

The CLS-class multi-beam headlamps of the Cedrus Mercedes-Benz have a total of 24 LEDs arranged in a grid pattern [53]. The LEDs have a light-emitting area of  $0.5 \text{ mm}^2$ . Each LED can emit a light flux of 90 lm. The gap in the LED package is closed by the main optical device to homogenize the LED light and project it onto the road. The gap of each LED can make its light spots just coincide, and the external geometric structure converges to achieve a higher level of overall system efficiency. The LEDs pass through a total reflection optical device made of a fiber-like silicone material. The light emitted by the LED passes through the external geometry of the fiber and aligns with the auxiliary lens. This fusion achieves a high overall system efficiency, which can produce 90 lx illumination output in 25 m with a pixel width of  $1.2^\circ$ . The two modules produce more than 195 lx of lighting output and reach a high beam range of 485 m. The brightness gradient between full-power pixels and darkened pixels passes through the auxiliary lens surface, and the target microstructure is optimized, thus the overall adjustment has a significant mitigation effect. The light distribution is divided in vertical and horizontal directions, and it is more inclined than the  $30^\circ$  tilt observed in the conventional low beam module to use vertical or right-angle tilt. This tilt is produced by the grid distribution pattern. The anti-glare, as shown in Figure 8, is realized by turning off the light in the designated area, and the effect of adjusting the light in the area can be achieved. Matrix LED headlamps can save the head by illuminating only the body of the object with a lower lighting array, meaning that they can draw the driver's attention to danger without dazzling people or animals in front of the vehicle.



**Figure 8.** Partial schematic diagram of multi-beam LED module with improved resolution.

Kim et al. fabricated an m-LED pixel array based on a flip-chip structure [54]. The array uses a photosensitive polyimide core dielectric layer to form multi-level metallization. This structure allows each LED in the array to be independently controlled. The spacing between individual pixels is  $115 \times 115 \text{ }\mu\text{m}$ , and there are a total of 256 LED pixels. Research

has found that, by reducing the pixel pitch to eliminate the dark area between pixels, it can be used as the light source of pixel car headlamps.

Reiss et al. clarified that, for highly clear glare-free and road marking functions, a highly pixelated automotive headlight system should be adopted [55]. Among spatial light modulators and pixelated LED solutions, it is currently the most reliable and optically efficient solution. For example, the field of view of a good road marking is  $15^\circ$  horizontal and  $10^\circ$  vertical, and the required resolution is  $0.1^\circ$ . In order to maintain good contrast, the light source needs at least 15,000 pixels. With a smaller number of pixels, this is achieved by changing the focal length of the optical system. Although the pixel resolution is low, road marking solutions with thousands of pixels provide good functionality.

Cladé et al. pointed out through comparative experiments that, when 4 k pixels are used for headlamp design, the glare-free area can be finely adjusted without the potential interference projection of light and dark contrast lines, and it can maintain a long-distance lighting field of vision while being illuminated at high speeds [51]. The car light model can provide a resolution of  $0.25$  to  $0.3^\circ$  in two directions within a complete angle range, which is much higher than the resolution of the human eye, and each pixel of the entire model is very uniform. The size of the glare-free area corresponds to the parameters of the lighting module. The pixel edge blur is defined as the same angular distance between 0.5 lx and half of the maximum intensity of the pixel. Through the pixel pitch, the position accuracy of the edge of the glare area makes the area larger. The glare area reduces the visibility of the edge, making the entire spot relatively smooth. Experiments show that, if 0–100% is used to deactivate or activate certain pixels, the light beam will produce disturbing unevenness. In order to reduce this discomfort, the brightness and the unevenness can be made by smoothly shifting the edge pixels. There are fewer junctions between dazzle, which makes the driver more comfortable. The indicator on the road can achieve refined light distribution through a large number of pixels.

Kim et al. initiated the SIMPL project to combine micro LED technology with display optics technology [56]. Due to the same width and height ratio, the light source being developed or to be released is not suitable for wide vehicle beam patterns. The central brightness of the beam pattern of the system exceeds 60 k cd, and the light efficiency exceeds 30%. At the same time, research has found that the resolution required is 0.1, FOV is a  $40^\circ$  horizontal and  $10^\circ$  vertical beam pattern, the number of LEDs is  $400 \times 100$  LEDs, each LED needs to be isolated from pixel crosstalk, and the spacing between each LED is  $40 \mu\text{m}$ . The projection part is used in the imaging optics engineering of the camera industry to project a clear spot. SIMPL can change any luminous flux within the range of  $\pm 20^\circ$  to achieve the low beam distribution required by ECE. The luminous flux is 315 lm, and the extended luminous flux is 500 lm. The high beam output luminous flux is 900 lm, and the extended luminous flux is 500 lm. The imaging system is designed using the imaging method in the camera. High-resolution LED pixel headlamps can reduce the dazzling of other road participants, optimize the light distribution to suit the driver's field of vision, and help improve safety.

Jonghun et al. proposed a pixel light source based on "wafer process and forming silicon on GaN" [57]. Pix LEDs are attached to a metal PCB and electrically connected by wire bonding. The chip has a total of 192 pixels, and the thermal characteristics are less than 1.3 k/w. Each chip is wire-bonded and packaged with silicone resin. The spacing between each LED is less than  $20 \mu\text{m}$ . The chip is characterized by its narrow shape. The dark area and the LES are relatively small, thus the pixel separation between each LED can be achieved without using a condenser lens. The heat dissipation is good, the contrast can reach 600, and the width is that of a single LED. It is  $4 \times 17.5 \text{ mm}$ , and the pitch is  $20 \mu\text{m}$ . The realization of high contrast is mainly by applying Si barriers between each LED pixel to suppress light diffusion. Compared with traditional headlamps, the corresponding light output can be realized by only switching the LEDs. The design flexibility is high, and customized design can be realized. At the same time, functions such as "single chip

multi-color” may be added in the future to adapt to extreme weather and improve visibility. The multi-color function in a single chip has great potential for automotive applications.

When the car detects that there is a car on the side of the road or on the opposite side, some of the lights will be turned off to prevent it from affecting other drivers. This technology also means that more information can be projected on the road, such as projecting guide lines or navigation suggestions on narrow roads. At the same time, it can also be used to warn the driver, providing a reminder of road conditions or construction sections ahead.

### 3.3. Existing Measures to Deal with System Stability of High-Resolution Headlamps

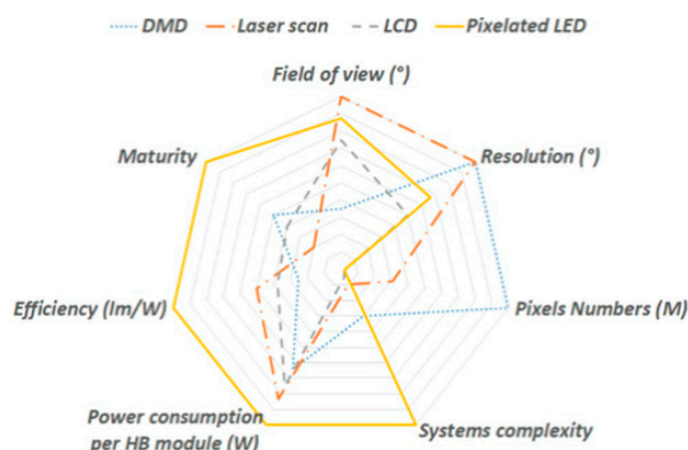
Joo et al. designed an adaptive driving beam that, in addition to common anti-dazzle functions, uses LED lights with adjustable color temperature to better alert the driver in bad weather conditions [58]. The developed ADB (6000 k~3000 k) illuminates the target object, and the visibility of the ADB is analyzed with the CL-500A luminometer. The size of the LED chip is  $1.1 \times 1.1 \text{ mm}^2$ , with 1400 lm under 1.5 A, and any one of them can meet the ECE R112 standard; the size of the PKG is 0.1 mm. The light emitted by the eight LEDs in the series array is collected through the first optical guiding lens, and then the light beam is secondarily distributed through the free-form surface lens and is transmitted to the second projection lens. The ADB spot covers  $\pm 2.5^\circ$  vertically and  $\pm 10^\circ$  horizontally. Using the simulator and the 16-channel LDM to control each LED, one can control 256 levels of dimming. Regarding LED array and light, humidity, rain sensors, etc., various sensors are synchronized, the weather conditions are analyzed through the sensor system, and the color temperature of each LED in the lamp is controlled in real time. The comparison test verifies that the average brightness of the 6000 k light source on the high-brightness reflectance sheet is higher than that of the 3000 k light source during normal road driving. Specifically, it is 26.7% higher. When driving on rainy roads, the average brightness of the 3000 k light source is 11.25% higher than that of the 6000 k light source. In snowfall, the visibility of the 6000 k light source is 12% higher than that of the 2000 k light source. It is confirmed that the system can provide safety impact.

Zhang et al. proposed a lighting system composed of an LED array and a lens array [59]. According to the principle of integral imaging, the mapping relationship between the source and the target was established. According to the mapping relationship, the shape of the light type can be adjusted freely, and a  $32 \times 32$  LED matrix was designed. The use of matrix lighting can achieve real time control of light beam and shape. The combination of LED array and lens array is also one of the more popular research directions. Knöchelmann explained that the small lens array based on the Kohler illumination principle can effectively homogenize the light and shape it into a rectangle at the same time [60].

By comparing the existing mainstream pixelated architectures—LCD beam, DMD, laser scanning, and pixelated LEDs, as shown in Figure 9—Beddar argues that pixelated LEDs have higher efficiency and longer service lives and help to reduce CO<sub>2</sub>. The emission is in line with the current concept of green environmental protection [61].

Li designed a matrix headlight based on artificial intelligence control [62]. The microprocessor processes the data received by the data acquisition module and controls the corresponding LED matrix control module, which is arranged in a matrix in the internal space of the car headlamps. There are four lighting lamps, and the infrared sensors are installed at the bottom these; the controller is connected with the mobile intelligent terminal through the communication board, and the connection with the control panel and the time unit is realized. The experimental results show that, compared with traditional car headlamps, the energy consumption of matrix headlamps is reduced by 16%, effectively reducing the energy consumption of car lights.





**Figure 9.** HD lighting technology: analysis of advantages and disadvantages.

### 3.4. Review on High-Resolution Headlamp Prototypes

The following review is based on the published prototypes of high-resolution headlamp and their features in the Table 1.

**Table 1.** Properties of published prototypes of high-resolution headlamps.

Title 1	Number of Pixels	Angular Resolution in °	Pixel Pitch in $\mu\text{m}$
LED array			
Gordon et al. [39]	$3 \times 11$	1.5	
Audi [40]	25		
Smatrix [41]	$3 \times 12$		
Hella [42]	84		
Pixel LED			
Osram [44,45]	$32 \times 32$	0.25	125
Trommer [46]	4096	0.25	125

With the development of miniaturization and intelligence of automobile styling, LEDs are widely used in the field of automobile lighting due to their high brightness, miniaturization, and functional integration. In order to maintain the specified luminous flux output of the system, the size of the LED light source will be scaled or increased accordingly to compensate for the low efficiency of the entire optical system, which requires the LED to have high flexibility.

The LED array has a small number of pixels and relatively low resolution, which can achieve basic far and near beam lighting and anti-glare functions. Additional colors of LEDs can be added to adapt to the disadvantage of poor white light penetration in bad weather. Each LED in the LED array needs to be controlled individually, which increases the size of the system and limits the number of LEDs. Improving optical efficiency and good thermal performance are the main challenges, which requires the LED array to be compact, which brings new challenges to the underlying technology. The integration of additional functions further promotes the miniaturization of the light source. At present, LED array-based modules generally use a dense secondary optical collection system and generally use a conical light collector or a silicone lens, which limits the volume of the entire system.

The new technology has increased the resolution to far more than 10,000 pixels. Due to the development of micro-LED technology such as micro-led, LED technology can be miniaturized to produce small pixels. Each pixel is closely spaced. The CMOS integrated electrical mutual pass switch can directly address each pixel, the resolution is less than that of the human eye, and it can make the car headlight project each pattern like a projector.

However, due to the immaturity of the chip manufacturing process, the main challenges are contrast and overall efficiency. The pixel size is small, but the optical separation space between the pixels is difficult to solve. The increase in operating current density will reduce the overall efficiency, and the edge pixel array the photon extraction combined with non-radiation will further reduce the efficiency. One method is to enlarge the pixels, but it will increase the cost of the system. In addition, the difficulties that need to be overcome are the need to change high LED fit and high production volume from the existing technical methods, the extremely high yield requirement, the defect control to avoid bad pixels, etc.

However, it is foreseeable that, with the development of technology, these challenges can be solved, and micro-led is currently the most effective and lowest cost technical solution.

#### 4. Conclusions

Car lights have witnessed the development history of automobiles, and vehicle lighting technology has continuously been innovated. With the development of automobile intelligence, the intelligentization of vehicle lighting has become a general trend. The pixel-based intelligent headlight system has been used in a large number of technological innovations in the field of sensors and algorithms, and, as a consequence, the car headlight system has its own “eyes” and “brains”, which can be combined with complex road environments pedestrians, vehicles, and other objects on the road. Intelligent calculations on the recognition are performed, then the light path is programmed, and the pixel level is controlled. There is no need for cumbersome adjustment operations by the driver. The pixel headlights can automatically judge and adjust the illuminance of far and near lights according to road scene, vehicle speed, and steering wheel angle, thereby comprehensively improving the safety of night driving.

With the continuous development of autonomous driving technology, in the next 20 years, new infrastructures for organizing large-scale urban traffic will continue to increase in number. Environmental aspects require the provision of high-efficiency and low-power solutions with optimized safety and a reduction of personal-based traffic volume, which will lead to a demand for simplified, reliable, and fully automated and controlled lighting systems. In the future, lighting will be capable of building a database based on real time information of vehicle driving, the surrounding environment, and traffic conditions and will automatically optimize the best lighting distribution.

LED pixilation is a major trend. Matrix LEDs are less than 100 pixels, and silicon lenses must be used. The current matrix LED system has a low resolution, and it struggles to project clear symbols on the road. The matrix LEDs module with more than 100 pixels is basically a single-chip package placed on the PCB, using the gap between the LEDs to achieve crosstalk prevention, but the existence of dark areas makes the spot unbalanced; this problem is difficult to solve, and the resolution is low. Although some LED matrix car lights with more than 1000 pixels solve the problem of resolution to some extent, they still cannot solve the problem of anti-crosstalk.

The main requirement for high-resolution pixel headlamps in the future is high-definition, that is, high pixel distribution, and the micro LED system is the key to this solution. MicroLEDs can overcome the shortcomings of matrix LEDs by aligning traditional discrete LED chips one by one and solving the problems of low contrast and scalability. Matrix LEDs are difficult to align with traditional discrete LED chips due to problems such as the offset between the chips and the distance between the rotation distortions. In contrast, pixel technology based on GAN technology of the Si LED on the sapphire substrate solves the problems of alignment distortion between chips and low contrast and low scalability. Micro-LED is the best choice for high-resolution pixel headlamps. With a small lens and module package, it can provide very comfortable and efficient lighting for roads at night to meet today's headlight design requirements. In addition to lighting, this system can also provide some basic image projection functions, such as highlighting simple patterns, information, and driving-related obstacles for the driver.

The next challenge of this technology is to increase the number of pixels per module to 10,000 to achieve a pixel pitch of  $0.1^\circ$ . The challenge lies in the research progress of the high-resolution pixelated LED itself, maintaining clear pixels, efficiency to avoid glare, and optical and electronic complexity of the module.

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