

Advanced Modeling Techniques for high performance and human centered LED lighting system

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Base on LEDs for high performance
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Abstract

Recently, the simulation of high performance displays and human-centered illuminance based on light-emitting diodes (LEDs) has become a hot topic in many research fields. LEDs can be found in advanced illuminance, large-scale displays, and other electronics. An efficient simulation can play a guiding role in interpreting the knowledge gained from operating an optical system. However, an optical system usually has a large number of parameters and contains a highly complex structure. Unlike some traditional physical quantities, many of the concepts in optics are complex and difficult to understand. The optical parameters may be of the scalar, vector or tensor type, and they may consist of multiple variables. Moreover, sometimes the optical parameters may relate to several different research fields, such as photobiology or photochemistry. Thus, the focus of this thesis involves the modeling of complex spatial optical systems and simulation of these types of large-scale and complex optical parameters.

Traditional modeling and simulation techniques in optics rely on one or two types of special software and are restricted to a single field. Thus, the interdisciplinary nature of research in the field of optics complicates modeling and simulation. This dissertation pursued multi-domain interactive applications using several software tools that are based on different research fields, such as optics, mechanical design and architectural design. Meanwhile, programming has also been used to aid modeling and computation. Both of these techniques have been used to solve practical problems based on two criteria: high performance and a human-centered approach.

For high-performance displays, we present a multiple-layered backlighting system in an advanced display domain. This new backlighting system can obviously increase the luminance flux of the backlight system in a limited space and save energy by using LEDs. The power is insufficient in a single-layered LED panel for some new display devices. However, the LED substrate is opaque, preventing rays from the rear layers from reaching the front, which is why the application of LEDs is limited not only in panel display systems but also in optical projection systems. This study probed this problem using lenses and LEDs, and we implemented a spatial multiple-layer LED backlight system. The hole in the LED panels and lens cause the light to radiate from the rear panel to the front panel by multiplying the radiation power. As a result, a high light output can be achieved. The entire model was simulated and tested with optical software that used the Monte Carlo ray tracing technique to describe the route of the

rays. After computing the transparent and missing rays, the illuminance maps were simulated to evaluate the light distribution. We also compared the results with those from a normal LED backlight system and verified that the proposed system is efficient in providing a high output light source. This advanced multilayered backlighting system can be used in 3D TV systems via stacked liquid crystal display (LCDs) which developed by MIT and in display devices used in a bright outdoor environment, such as a cell phone under sunlight.

For human-centered displays, we propose a new blue light hazard-reduced backlighting system to maintain a high performance and to reduce the hazard from the light source, especially from the LED, which can harm human eyes. Because the LED is widely used as a light source in backlighting systems of display devices, the serious blue light hazard in white LEDs has been recognized by more and more researchers and manufacturers. Many manufacturers have begun to take a series of countermeasures for this. Most countermeasures have focused on reducing blue light via software technology since it is easy to actualize and requires almost no cost. However, there are two manufacturers that have insisted on a hardware method to reduce the blue light hazard that also maintain the color performance. In this paper, we have proposed a new method for reducing blue light via hardware and evaluated both their methods via software and hardware using numerical analysis. The new design is based on a backlighting system in which the original white LED was modified so that the blue-band energy was reduced by 50% and in which cyan light LEDs were added among the white light LEDs. Then, we optimized and adjusted the distribution of the LEDs' energy to reduce the harm of the blue light while also maintaining good color performance. The results show that our system can both reduce the blue light hazard and maintain the color performance by adding cyan LEDs.

Finally, with regard to human-centered illuminance, we concentrated our research on a high beam lamp. An adaptive reflective sheet was proposed to improve the energy efficiency. We confirmed that it is useful for a certain illumination distance via our simulation results of the luminous flux and illuminance. Another original simulation experiment was performed to analyze the optical transmission of the high beam under low visibility weather conditions as a function of different correlated color temperatures. Based on real mist data and our hypothesis of lower transmission of light with a low color temperature in fog, the high beam was confirmed to have a higher efficiency than the high beam with a high color temperature. According to this conclusion, a double rotatable color temperature high beam lamp that can be used to solve the contradiction

of high transmission in bad weather and better vision performance in good weather was proposed.

Chapter 1 Introduction

Traditional light sources, such as incandescent lamps, were the first electric lamps. An incandescent light is an electric light that has a wire filament heated to such a high temperature that it glows with visible light (incandescence). The filament, which is heated by passing an electric current through it, is protected from oxidation via a glass or quartz bulb that is filled with an inert gas or is evacuated. Incandescent bulbs have been replaced in many applications by other types of light source, such as fluorescent lamps or LEDs.

The fluorescent lamp is another important improvement in light sources. A fluorescent lamp or a fluorescent tube is a low-pressure mercury-vapor gas-discharge lamp that uses fluorescence to produce visible light. The fluorescent lamp converts electrical energy into useful light much more efficiently than incandescent lamps. The typical luminous efficacy of fluorescent lighting systems is 50–100 lumens per watt, which are several times the efficacy of incandescent bulbs with a comparable light output but less than that of a typical LED. However, with the development of lamps in recent years, the luminous efficiency of fluorescent lamps can reach 100–150 lumens per watt, which is even beyond the luminous efficiency of some types of LEDs.

The LED has been considered to be the second revolution in the field of lighting since lamps were invented a hundred years ago. Currently, if you look around in your daily life, you may find LEDs everywhere. Although all illuminated light sources may not be LEDs and are instead fluorescent or incandescent lamps, you will surely find an LED behind your cell phone or monitor. An LED refers to a two-lead semiconductor with a P-N junction diode that emits light when it is activated. It can be regarded as a new type of solid light source that has many advantages, such as a long lifetime and a high efficiency. Currently, with the development of science and technology, more and more LEDs can be found in many fields, such as for displays (e.g., large scale LED display screens, backlight systems), illumination (e.g., desk lamps, headlights, etc.), visible light communications and so on.

With changes in society, people pay more attention to the technology related to their own needs than to scientific revolutions, such the theory of relativity or quantum physics. Large technical companies, such as Apple or Microsoft, engage in developing new technologies that are human centered and that have a high performance, such as

the iPhone or Windows 10. However, more and more design companies and academies have begun to emphasize vision in the design process since people rely on their vision to obtain information much more than before. Due to the small size and high efficiency of LEDs, they have been used both in consumer electronics and decorative designs.

However, few people know the details of light or vision and how LEDs have changed our lives. Unlike an object we can touch or a voice we can hear, light is an abstract concept that is difficult to understand. Meanwhile, unlike a voice (mechanical waves), light is an electromagnetic wave with a wave-particle duality. Thus, the properties of light are complex. This paper focuses on the field of applied optics, and our study used the ray tracing technique to help understand the nature of light and how it works. The ray tracing technique was combined with computer-aided design (CAD) to simulate some models based on several specific applications.

For the first application of LEDs and simulation techniques, we chose a backlighting system that plays a vital role in display systems. From a large-sized flat TV to a small-sized cell phone, LCDs occupy a large share of the market. Although some new panel display technologies, such as the OLED or E-link, have appeared, they cannot replace LCDs yet because they have not been fully developed. However, for a panel display system, a LCD cannot work by itself because it cannot be self-luminous. The backlighting system is the other part of the panel display system, and it is used to support the LCD by providing the light source. Traditional backlighting light sources used cold cathode fluorescent lamps (CCFLs). These new types of fluorescent lamps have many advantages, such as a high efficiency, high illuminance and low power consumption. These advantages have allowed them to be widely used in many fields. Before LED products entered the market, CCFLs almost entirely monopolized the entire market of backlighting light sources. Until now, the price of CCFLs has been even lower than LEDs. The only reason why CCFLs have been significantly replaced by LEDs is because its two obvious disadvantages cannot be overcome. One is the high working voltage, and the other is the short lifetime. A high working voltage not only is dangerous to users but also affects other electronic devices. Regarding lifetime, the theoretical lifetime of LEDs is 10 times as long as for CCFLs. In addition to these two obvious disadvantages, another factor that has become more important recently is the size of the light source. Regardless of whether it's a notebook PC or a cell phone, people now are choosing to pursue lighter and thinner products. One can be amazed by the new products, such as the MacBook or iPhone, and we call this human centered. However, our first research in this field did not focus on lighter or thinner technologies; instead,

we focused on high performance. With the development of display devices, people no longer are content with two-dimensional (2D) displays. Three-dimensional (3D) has become a hot word in current society. Half of films have used 3D display device technology, such as Avatar in 2009. However, unlike a 2D display system, which is dominated by a flat panel display, 3D display technology presents a trend of diversification. 3D films that we watch in the cinema are a relatively mature 3D technology. However, the sacrifice is the user experience. This technology requires viewers to wear special glasses to watch a film. In addition to the discomfort of wearing this special type of glasses, it also is very inconvenient for nearsighted people who must wear double glasses or must change contact lenses and then wear the 3D glasses. However, the mechanism of this technology projects two different images to the same screen, and when the reflected light reaches your eyes, the two lenses of the glasses project the two different images to your eyes via the anaglyphic 3D technique or the polarized 3D technique [1]. Then, the two different images can be combined in your brain and can be reconciled; our brains will automatically synthesize two images to form a stereoscopic image. During the processing, our brains are equivalent to the CPU of computer, and this processing can cause an uncomfortable headache. Therefore, many researchers are pursuing other 3D technologies that are glasses-free. Among these glasses-free 3D technologies, there has been phenomenal research developed by MIT and Keio University. Both of them use more than two layers of LCD panel to obtain glasses-free 3D images. However, since the LCD transmission is very low, primarily at 10–15%, when the light from backlighting reaches the second or additional layers of the LCD panel, the luminous flux will tail off to $10\%^2-15\%^2$ or $10\%^n-15\%^n$ (n is the numbers of layers). To solve this problem, we proposed a multiple-layer backlighting system. However, the LED substrate is opaque, depriving rays from the rear layers of the possibility of reaching the front, which is why the application of LEDs is limited not only in panel display systems but also in optical projection systems. This paper probes this problem using lenses and LEDs and implements a spatial multiple-layer, LED backlighting system. The hole in the LED panels and lens causes the light to radiate from the rear panel to the front panel by multiplying the radiation power. As a result, a high light output can be achieved. The entire model was simulated and tested using the optical software, Tracepro, which can use the Monte Carlo ray tracing technique to describe the route of the rays. After computing the transparent and missing rays, the illuminance maps were simulated to evaluate the light distribution. We also compared the results with a normal LED backlight system and verified that the proposed system is efficient and provides a high output light source.

For the second application of LEDs and the simulation techniques, our research focused on the human-centered aspect. The backlighting system was also the object of our research. However, unlike the first part of the research, the second part did not pursue the high output of the backlight, but instead focused on blue light hazard reduction. With the development of optical technology, photobiology has become a hot field with increasing recognition. Traditional ideas considered light to be only used to illuminate to provide a visible scene for humankind. Meanwhile, light has also had a significant influence on plant growth via photosynthesis. However, more researchers have found that light also has a significant impact on the human body. At first, some scientists noticed that a long-term lack of light can make people depressed. Then, scientists further found that light has another impact on the human internal clock. Finally, scientists found that light has an effect on the growth of human cells and hormone secretion.

The hazard from blue light is one of the effects on the eyes in the human body. The eye is one of the most essential organs in the human body, and it is also vital for obtaining information. Among the electromagnetic spectrum, many bands of electromagnetic waves do damage to the human body, especially electromagnetic waves that have a short wavelength, such as gamma rays and ultraviolet. However, even in the visible spectrum, blue light with a short wavelength can also damage the human eye. Thus, in recent years, many international symposiums have considered photobiology safety as a hot topic.

With the global high-speed development of information technology, the media industry as the carrier of information has dominated the information dissemination process, and the status in society highlights the specificity of media industry. Display devices are the core equipment of the media industry. People spend much time reading from a panel display device and looking at a computer monitor, and there exists a potential crisis due to the blue light hazard among these display devices. In this paper, we developed new technology to reduce the blue light hazard using the ray tracing technique and numerical analysis to evaluate the effect of some existing methods for reducing the blue light hazard. Then, based on these methods, a new method of reconstructing a backlight is proposed.

One serious problem with reducing the blue hazard is that when the blue light hazard has been reduced, part of blue light in the spectrum of visible light is also decreased or prevented. The color performance of a display device will also be reduced. The most

obvious manifestation is the decrease in illumination and the yellowing of the display device. The main aim of our research was a balance between reducing the blue light hazard and maintaining the color performance. This was accomplished by adding a cyan LED, which is a lower optical hazard, to the backlight light source. The color performance can be maintained in the simulation result using some essential optical parameters, such as the color temperature and color rendering index.

Finally, we focused on the application of LEDs and simulation techniques. We changed our research focus to a high beam lamp with a backlighting system. Unlike the backlighting system, the headlight of an automobile is more similar to our needs in daily life. A high beam lamp is a special type of headlight that can be used in automobiles. Another commonly used headlight in automobiles is a low beam lamp. However, although they are very similar, the high beam lamp has received more attention compared with the low beam lamp.

Currently, more people are tending to replace their high beam lamps with auto tuning to meet their own needs for different purposes. However, few people want to replace their low beam lamps since few factors can be significantly changed due to this replacement. Due to the long illuminate distance of a high beam lamp, two factors are important for high beam lamps. One is power efficiency, and the other is light transmission.

Since a high beam lamp is used to illuminate far distances, primarily from 50 m to 100 m, some special high beam lamps may designed to illuminate more than 100 meters for a special purpose, such as for automobiles that always drive in areas that have mist, fog or rainy weather. Because the scattering of light will decrease the power efficiency of long-distance light transmission and because the light transmission may be decreased by the effect of different weather conditions, such as mist or fog, the high beam lamp is more important than the low beam lamp.

To evaluate the power efficiency, we built a model of a high beam lamp based on a real product, the H7 high beam lamp. From the structure of the H7 high beam lamp, we determined that much energy is wasted by the low reflectiveness and basement of the light source. Meanwhile, by modeling the high beam lamp, we also found that the focal distance of the reflector is very short, which means the emitted point is much closer to the bottom of the reflector and basement. Most of the light source is spherical, especially the light source used in a high beam lamp. Most of the energy emitted

backwards is lost because a large part of the energy is emitted to the low reflective basement. To solve this problem, a flat reflective sheet was proposed, which is easy to install and improves the power efficiency of the high beam lamp by reflecting the light that is emitted to the basement backwards. By analyzing two models of high beam lamps with and without a reflective sheet, the proposed sheet was determined to be effective for improving the power efficiency via the simulation results of these models.

Then, a second experiment was performed to analyze the light transmission of the high beam lamp. Color temperature is a significant index that can be used to evaluate the color performance of white light. High color temperature light is called a cold color, whereas low color temperature light is called a warm color. High color temperature light has been widely used in high beam lamps, and some new light sources have been developed in the market, such as xenon lamp and LEDs. Additionally, people tend to use high color temperature light to replace low color temperature light in high beam lamps since the color performance is much cooler than low color temperature light. As an example, if you want to present the beauty of a diamond, you would absolutely use high color temperature light to demonstrate its shining and fashion since the color performance is the same as sunlight at noon. However, low color temperature lights are always used in museum or religious halls, such as in temples and churches, because the color performance of low beam light is the same as that of a candle, which was widely used in ancient times long before the electric lamp was invented, and reflects the solemn atmosphere. However, few people want their cars to be viewed as an antique; instead, people want their cars to be shining and fashionable, just like a diamond. Thus, many reflectors have been designed to scale structure, and the purpose of this structure is not only to improve the concentration of the reflector but also to promote the shine and beauty, such as in multi-faceted diamond cutting.

However, low color temperature requires a higher light transmission than high temperature in bad weather conditions, such as on a foggy or rainy night. This idea has been recognized by the vast majority of people, especially drivers. Furthermore, many professional manufacturers have also launched specific products to address this issue, such as the fog breaker from OSRAM. However, we can find no data or parameters to prove the idea that low color temperature requires a higher light transmission than high temperature on foggy or rainy days, and the explanation for this idea lacks details. In specialized research, we even found two academic papers that came to the opposite conclusion. The objective of this research was to verify this idea using modeling and simulation techniques. First, we built different color temperature high beam lamps as

models for car lamps. Then, we adjusted the model of spectral attenuation and imported it into the light transmission model. Meanwhile, the car model with different color temperature high beam lamps was imported and a simulation via ray tracing was performed.

The data used in the spectral attenuation model was experimental mist data from the German Aerospace Center. However, according to the simulation result, we concluded that the transmission of low color temperature and high color temperature high beam lamps are almost the same in misty weather conditions. However, under other weather conditions, such as fog or rain, since water vapor particles and dust are a larger size and have a higher density, the effect of diffraction of different wavelengths becomes larger. Accordingly, the transmission of these two color temperature lamps may be altered when the low color temperature high beam lamp works better than the high color temperature high beam lamp. Based on this hypothesis, we assumed that the light transmission in fog is 10 percent that in the mist. By using these new data, we analyzed the transmission performance of the two color temperature high beams at different distances, which included a luminous flux and an average illuminous. The result showed that at a long distance the low color temperature high beam worked better than the high color temperature. Finally, we propose a new double rotatable color temperature high beam lamp that can be used to solve the contradiction of high transmission in bad weather and good color performance in good weather.

A comparison between the low color temperature and high color temperature not only addresses the concept of high performance, which assumes the use of a bold color high light in good weather conditions with a high performance, but also avoids the dangers of low visibility during bad weather by using low color temperature high beam lamps that have a high transmission and are human centered.

Research overview

The advent of new light sources has declared the herald of the era when mankind started to pursue quality lighting, such as high performance lighting and healthy lighting, instead of being contented with the traditional functions of lighting. A similar case in point goes to the purpose of technological advancement being shifted gradually from satisfying the needs of man's survival and development at the very beginning to, posterior to the satisfaction of those needs, improving human existence and perfecting their quality of life. Both of these cases embody the concept of people-oriented science and technology.

Just like integrated circuit and large integrated circuit which have replaced traditional electron tubes and transistors, the birth of LED as a new type of light source constitutes another revolution in the field of mankind's lighting technological development of far-reaching influence. Its low-power consumption, high efficiency, long-term durability, and integration capability, together with many other advantages, have made LED a popular substitute for traditional non-solid light sources and thus a leading role in the field of lighting and its application. Centering on the lighting system of LED, the current dissertation revolves around the key concepts of high performance and people-orientation of LED.

First of all, as a solid light source capable of miniaturization and integration, LED promises a larger space for design and application compared with large-size traditional light sources of intricate and vulnerable structure such as incandescent light and fluorescent light. Moreover, the some improved versions based on traditional light sources have made no further adjustment other than arraying LEDs, such as the array LED backlighting system in liquid crystal display screens and the like. Nevertheless there includes multiple layers of panels in the integrated circuit, some of which even constitutes the spatial integration of as many as ten panels. Yet due to the intrinsic features of light propagation, traditional concepts generally deny the application of spatial multiple stacks into structures like backlighting system, thus resulting in single-layer structure in all backlighting systems. However, a break from the tradition, the current dissertation toppled the traditional concept and made an innovative proposal- a spatial multiple-layers of backlighting system which resolved the riddle of spatial integration of backlighting system via the application of integrated LED and the pairing of holes and lens between panels. The dissertation, on the basis of advanced modeling

technique, designed a precise model of spatially integrated LED system, simulated as well as optimized the system using a professional software for optical analysis, resulting in LED backing system of spatial stacking consistent with the original conception. The system, with its transmission much improved, has ushered in the possibility of more advanced applications such as naked-eye 3D display system with stacked MIT multiple-layer LCD panels, tablet display system similar to HDR of Sony Z9D, as well as high-luminance tablet display system under the reflection of strong daylight.

Meanwhile, the current hot issue of photo biological safety has prompted scholars in this field to attach more and more importance to the ever-increasing application of LED as a new type of light source, especially in the area of the blue-light hazards of LED. At present, in-depth research in the field is being conducted by a considerable number of European and American scholars including those at Harvard Medical School. Moreover, in recent years, a group of ophthalmologists in Japan have founded the Blue Light Society targeting at blue light hazards. However, most of those research focused on the causes of blue light hazards, with relatively limited research attention on the prevention and treatment. The dissertation, from the perspective of lighting technology and the concept of people-orientation, mainly discussed and delved into the prevention and treatment technology of blue light hazards. Firstly, it conducted a quantitative analysis of blue light hazards using modelling and simulation of the existent software and hardware methods. Having elicited the conclusion that the hardware method of blue light prevention is superior to the software approach, the dissertation compared the two existent hardware techniques and proposed a new hardware to prevent blue light-increasing color-complementary cyan LED on the basis of incorporating traditional way of filtering blue light, which decreases blue light while preventing color excursion and the correspondingly sacrificed display effect caused by the lack of blue light in the spectrum. Via comparing the models and simulation computations, the dissertation furthered the optimization computation and analysis of the new structure using the optimizing technique, resulting in the theoretical model which decreases blue light hazards while maintaining the original color performance.

Lastly, apart from the research on backlighting system, the dissertation also analyzed the case of car lamps- one of the many fields where LED is adopted as traditional lighting system, with high beam lights (more often than not the focal point of car lamps) as the key area of analysis and structural design. Firstly, the dissertation took advantage of light utilization so as to propose further addition of reflector plate in the traditional reflector bowl to improve the luminous efficiency, followed by modelling and

simulation analysis. Meanwhile, the model was imported to car model of real-life simulation in order to test its practical efficiency and obtain high performance results. On the other hand, the dissertation conducted an analysis of light color temperature of car lamps including the performance of high beam lights of high and low color temperatures under various weather conditions. Via modeling and simulation, the dissertation adopted quantitative analysis and confirmed the traditional concept that the penetrating power of high beam lights of low color temperature in low-visibility weather conditions such as raining and foggy days is superior to that of high color temperature. At the same time, the model of high beam LED light switchable between two color temperatures was proposed to realize the concept of using high color temperature lights which have better color performance similar to that of sunlight under normal weather conditions while adopting low color temperature lights with powerful light penetration under extreme weather conditions like rain and fog. More importantly, modeling and simulation have confirmed its feasibility.

Utilizing Tracepro, the professional light source design and analysis software, and Solid Edge- the more convenient as well as professional machine design and modeling software, the dissertation proposed a series of intricate and innovative models which were then analyzed comprehensively via computer analysis techniques such as the Monte Carlo ray tracing technique and optimization design and further modified based on the analysis results. All the research work stemmed from the prerequisite of high performance as well as people-oriented concept. Just like the fact that iPhone is a huge success and has penetrated into people's life owing to its high performance and people-oriented concept instead of its technological invention, people-oriented innovative research and application, it is hoped, can bring about revolutionary facets into people's life.

Technological preparation

Optical engineering software

Optical engineering software is a kind of computer aided design software used in the field of professional optical system design. It uses the computer and its graphics equipment to help the designers to improve their work. Through the computer for different programs or models of a large number of simulation calculations, analysis and comparison.

Tracepro is kind of professional optical engineering software which be used across many industries for opto-mechanical design and analysis. Major applications include: Light Pipe Design, Lighting, Aerospace and Defense, Automotive, Display Design, Consumer Electronics, Medical and Life Science and Stray Light.

Comparison of the software

Currently on the market there are many kinds of optical design software, they all have their own advantages and disadvantages. So how to choose the appropriate optical design software according to our own needs is important at the very beginning of the work.

First, optical design software can be divided into four major application areas, which are Imaging optics, Illumination optics, Photo-communication, Thin film optics. Table 1 shows different application areas of some typical optical engineering software.

Table 1 Typical optical engineering software to be used in different application areas

Application Software	Imaging optics	Illumination optics	Photo- communication	Thin film optics
Tracepro	△	○	×	×
Lighttools	△	○	×	×
OSLO	○	△	×	×
Zemex	○	△	×	×
CODE V	○	△	×	×
Optiwave	×	×	○	×
TFCalc	×	×	×	○
Filmstar	×	×	×	○

Second, in this paper, all of our studies are developed around illumination systems. Therefore the optical design software which major applied in illumination optics should be specific discussed. In the application area of illumination design software, more than four software have been used such as Tracepro, Lighttools, ASAP and ODIS. However, the most powerful and also the most famous two are Tracepro and Lighttools.

Table 2 Functional comparison of Tracepro and Lighttools

Functional comparison Software	Simulation Speed	Modeling Ability	Modifiability	Optimization	Appearance of analysis chart	Analytical skill
Tracepro	○	○	○	△	○	△
Lighttools	△	△	△	○	△	○

Tracepro used in our research

In our research, complex multiple layers illumination model has been proposed, therefore, high modeling ability and modifiability is most important. Meanwhile, due to the large amount of calculation on the multiple layers illumination model, simulation speed is another significant consideration here. As function of optimization, we used Matlab but optical engineering software to do the optimization of the calculation. Based on these reasons and the comparison of two software in Table 2, we choice Tracepro but Lighttools for optical design and simulation.

On the other hand, Tracepro uses the built-in CAD user interface to analyze the energy flux that travels through optical or lighting systems. Its main purpose is to show the energy from the light source through any optical, lighting system after the radiation / illumination or luminous intensity diagram. By non-sequential ray tracing of points and directions (Monte Carlo method), we can analyze the energy loss, absorption, reflection, refraction, scattering or polarization at any point in the system, shows in Fig.2. Meanwhile user interface is very easy to use, and allows the use of the mouse to move objects, generate objects or modify objects with Boolean operations.

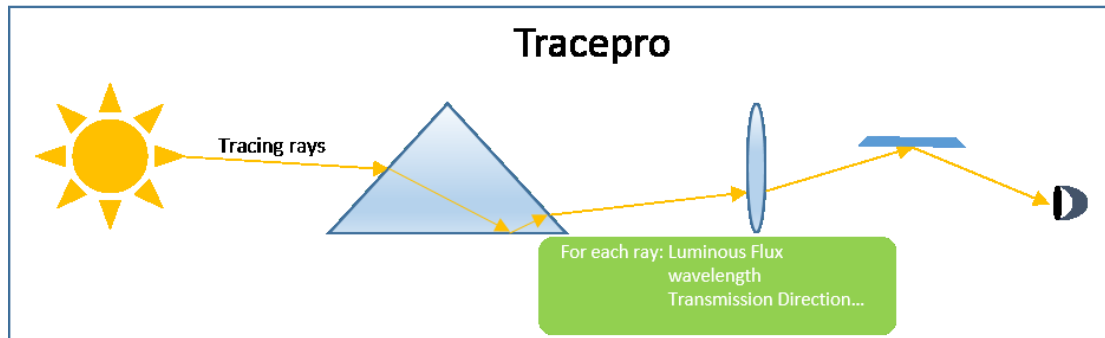


Fig 1: The demo of ray tracing by Tracepro

The advantage of TracePro is that it can import or export many different CAD formats, including SAT, IGES, STEP and STL. TracePro CAD integration of the optical design data, simulation of the real world. TracePro is a full-3D virtual prototyping system that takes into account anything that might happen in real-world simulations. Users create geometry either by using the native TracePro CAD interface or by importing models directly from mechanical design program such as Solid Works, Pro/ENGINEER, Solid Edge, Autodesk Inventor or other CAD product that exports IGES or STEP models. In our research we used both native TracePro CAD interface for modeling of simple structures and importing models directly from Solid Edge which have complex structures. However, currently OSLO can only output IGES file format, the input file format only Code V and Zemax optical design files. Meanwhile OSLO is a spreadsheet interface which is hard to master and visualization analysis. On the contrary Tracepro's CAD interface can be learned quickly and can be observed in the optical and lighting systems where the problem is located.

At last, the thesis of our research is “Advanced Modeling Techniques for high performance and human centered LED lighting system”. In this research, more than three software have been used alternately (Tracepro, Solid Edge and DIALux) even the simulation results of DIALux have not been added into the papers. Although they belong to different fields, the interface of modeling is the same which both based on 3D CAD, and the data of model even some specific parameters can be easily transported from one to another. Meanwhile our research covered at least three major applications such as Lighting, Automotive, Display Design, Medical and Life Science.

Chapter 2 Related works

2.1 Multiple layers of the illumination system

Since LCDs have grabbed the majority share of the market, the backlighting system has been under intense research along with the development of the LCD. Several years ago, CCFLs dominated the backlighting market. However, as the price of LEDs decreased, they have replaced CCFLs, and LEDs have become almost the only light source in backlighting systems.

There also some new light sources that have been designed to challenge the leading position of LEDs in the backlighting arena, among which lasers are conspicuous [2]. Lasers are different from LEDs, even if they are endowed with the same lifetime durability. The most obvious characteristic of a laser is its monochromaticity, which enables the semiconductor of a RGB laser to present a better color gamut than an LED. However, taking the cost, stability and many other factors into consideration, lasers are no match for LEDs.

The multitude of research work in the arena of backlighting systems revolves around two sub-fields: LED backlighting and backlighting modules.

Unlike a light source, a backlighting module functions to increase the operation rate of light. The backlight module is mainly positioned in the middle of the LED panel and LCD. The operating principle of liquid crystal molecules is to turn on/off the rays directed into the pixel dot. Research has shown that when rays under the condition of oblique incidence are directed into a liquid crystal molecule, the function of turning on/off is decreased [3]. Based on this characteristic, the backlighting module mainly includes a brightness enhancement film (BEF), a diffuser plane (DP), and a diffuser sheet (DS) [4].

Studies on LED backlighting are the other major concern for backlighting system research. Unlike the backlighting module, the LED is a light source that plays a crucial role in displays. To support the LCD, there are two ways of installing LEDs for liquid crystal panels that are currently dominating the backlighting market: a direct backlight (light box) and an edge-light or a light-guide-based backlight [5]. As the names suggest, direct backlighting involves installing an LED directly behind the liquid crystal panel,

allowing the rays from the LED to go directly into the panel. However, an edge-light backlight involves installing LEDs at both sides of the liquid crystal panel and then illuminating the liquid crystal panel through the light guide panel (LGP) [6]. These two methods have their respective advantages and disadvantages. Direct backlight, used to decrease the thickness, uses LEDs with a small chip size, making the cost more than that of the edge-light for the same sized LCD. In addition, the efficiency of the small chip-sized LED is also inferior to high efficiency LEDs, which have a larger chip size [7]. However, the uniformity and dynamic color performance are better than the edge-light backlight because LEDs can be individually controlled by the panel.

2.2 Photobiology safety

There has been much research that has focused on the evaluation of blue light hazards on humans. Researchers have conducted many physiology experiments to clarify the mechanism of the blue light hazard, such as the paper published in 2015 by Harvard University [15]. For example, the effect of blue light LED on melatonin suppression and how display manufacturers can determine how their products will affect melatonin levels has been discussed [16]. In another study, the blue light from LED elicited a dose-dependent suppression of melatonin in humans [17]. One of the most important issues that we are concerned about is the blue light hazard to our vision, and one study clearly demonstrated the relationship between blue light and age-related macular degeneration (AMD) [18]. Meanwhile, other studies have performed experiments to explore the effect of blue blocker techniques on humans, such as blue blocker glasses on male teenagers [19]. However, this research focuses on the technology of blocking blue light hazard.

LCD is widely used in three areas: for mobile phones, computer monitors, and LCD TVs. They are easier to install and use third-party software. Currently, the most popular software to cut down blue light on computers include f. Lux and Redshift, whereas there are more applications on mobile phones and the effect is almost the same in both platforms. Their main principle is to adjust the color palette of the blue pixel values via software to reduce the blue light. Other research has focused on controlling the display characteristics through changes in luminance and CCT to reduce blue light [20].

In terms of blocking blue light using hardware, there are two main methods according to a latest study. These methods have been developed by professional production companies of displays and have been successfully launched to market. Both methods

first defined a specific spectral band of blue light hazard and process the light using hardware. The two companies are professional monitor manufacturers, BenQ and AOC.

Specifically, AOC changed the backlight module of the white LED phosphor powder composition so the entire spectral band shifts toward the long-wave direction. Some research has described the method of changing the phosphor powder [21]. The identified blue spectral peaks were moved from the original band at 444 nm to 460 nm, thus avoiding the most harmful band of 400–450 nm and filtered the blue light. Research that has shown that 420–453 nm blue light will do harm to human skin [22]. Another study even extended the band of wavelength to 480 nm, which is the cyan color, to analyze the blue light irradiation on human dermal fibroblasts [23]. However, the method used by BenQ directly cuts part of the blue light below 455 nm using hardware, and it retain the energy of blue light over 455 nm to filter the blue light.

2.3 Illumination on automobiles

Nany researchers have focused on automotive headlamps. They have been mainly concerned with three factors: the photics, thermotics and electrics. Since the headlamp is high-powered electronic equipment, the circuit design and thermal design are essential. In recent years, Jiangsu University has performed much research related to automotive headlamps. They have analyzed the optical characteristics of high beam lamps with not only ellipsoid-like reflectors but also condensing lenses. Additionally, they have created a circuit design for their high power LED head-lamps, and simultaneously designed a cooling device system for it [32]. Then, they used finite element analysis in their thermal design of the automotive headlamps, as published in two papers in *Applied Thermal Engineering* [33] and *Microelectronics Journal* [34].

However, some researchers have focused on the visibility of driving. Papers have been published in the International Technical Conference on the Enhanced Safety of Vehicles (ESV) [35] and Society of Automotive Engineers (SAE) [36]. In these two papers, they considered that effect of CCT on the visibility of driving using objective and subjective methods. The empirical method involved measurement via vehicle instrumentation and optical instrumentation. The subjective method included both males and females in older and younger groups. The only main difference in their research was the type of CCT used in the experiments. However, their conclusions were the same. Their results indicated that the effects of CCTs on objective and subjective variables are not robust relative to the range of differences associated with the visibility of driving.

Chapter 3 Scalable LED

3.1 Background

Currently, light emitting diodes (LED) have replaced cold cathode fluorescent lamps (CCFL) as backlighting systems in liquid crystal displays (LCD). However, the original single layer alone can only satisfy the needs of the panel display and cannot satisfy the requirements for a 3D display system or outdoor displays. In this paper, a new method is proposed to demonstrate that a high output can be achieved using spatial stacking of integrated LED light sources. Moreover, we also simulate the system and measure the light output and the distribution of the light. The system is efficient to provide high luminance while keeping a balanced light distribution. With this proposed high luminance spatial multiple-layer LED back-lighting system, many requirements, especially for the high light source, are supposed to be satisfied.

Recent years have witnessed the advent and employment of new types of display systems, among which plasma display panels (PDP) had previously shared almost the same market with liquid crystal displays (LCD) but finally failed. Currently, we are looking forward to organic light emitting diodes (OLED). However, LCDs have occupied the biggest market and have been renewed.

Unlike PDPs and OLED, an LCD cannot emit by itself. The backlight plays a vital role in the LCD display system. The market of the display arena requires a lifetime, high-output light source. Taking environmental protection and energy saving into consideration, light emitting diodes (LED) constitute the best choice.

In certain fields, where small, compact light sources with high power of radiation are in demand, super high pressure mercury lamps cannot be replaced by LEDs, even when multiple LEDs are arrayed. Some projector manufacturers are dedicated to developing a novel integrated light source with combined LEDs and lasers, which can replace super high pressure mercury lamps. However, this technique is expensive. In addition, its safety risks have aroused mounting concern, as exemplified by America and Europe's verdict of not granting permission to its application. In addition, with the development of 3D imaging systems, traditional pixels have evolved into voxels, upgrading the resolution into three dimensions. Chances are that the technique has not been widely applied outside the laboratory in 3D holographic imaging or 3D TVs via stacked LCDs

[1]. Moreover, the power is insufficient in a signal-layer LED panel. However, the LED substrate is opaque, depriving rays from the rear layers of the possibility of reaching the front, which is why the application of LEDs is limited not only in panel display systems but also optical projection systems.

This paper probes this problem using lenses and LEDs and implements a spatial multiple-layer, LED backlight system. The hole in the LED panels and lens makes the light radiate from the rear panel to the front panel by multiplying the power of radiation. As a result, a high light output can be achieved. The whole model is simulated and tested with the optical software Tracepro, which can use the Monte Carlo ray tracing technique to describe the route of the rays. Upon the completion of computing transparent and missing rays, the illuminance maps are simulated to evaluate the light distribution. We also compare the results with the normal LED backlight system and verify that the proposed system is efficient to provide a high output light source.

3.2 Proposed Method

3.2.1 Stacking Multiple LED Panel

LED panels are opaque. If we stack several layers of LED panels spatially, the rays from the rear are bound to fail to reach the front. A solution has been proposed and is shown in Fig 3.1.

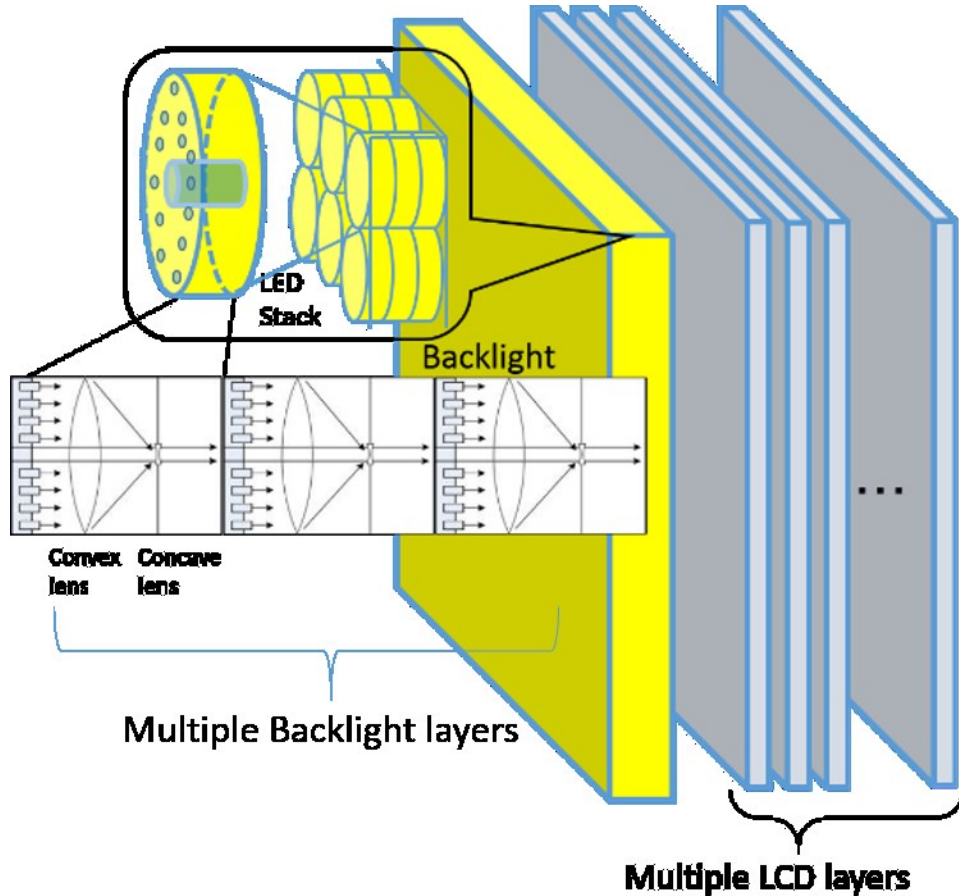


Fig 3. 1: Stacked LED panel and LCD panel

Because the transmittance ratio of LCDs is very low (10~15%), stacked LCDs, which can be used as 3D display, requires much more luminance than usual. This stacked LED applying concave lens panel has been proposed to solve the problem. The convex lens is used to gather the rays from the LED, followed by the concave lens to turn these rays into collimated light and through the hole to the next LED panel.

3.2.2 Choosing Types of LEDs

LEDs can be classified into many types based on shapes and numbers of cores. Surface mounted devices (SMD) and dual inline-pin package (DIP) are the different shapes. If we use white LED for the illuminance, the LEDs can be divided into one-core LEDs and three-core LEDs. However, there is some research on more than three cores for LEDs for some special purposes [8].

Because of the advantages in terms of thickness and wide emitting angle, most LCD backlighting has adopted SMD LEDs.

To test the performance of SMD in this method, a single-layer SMD has been combined with a convex lens. Fig 3.2 shows the simulation result of the SMD and convex lens array.

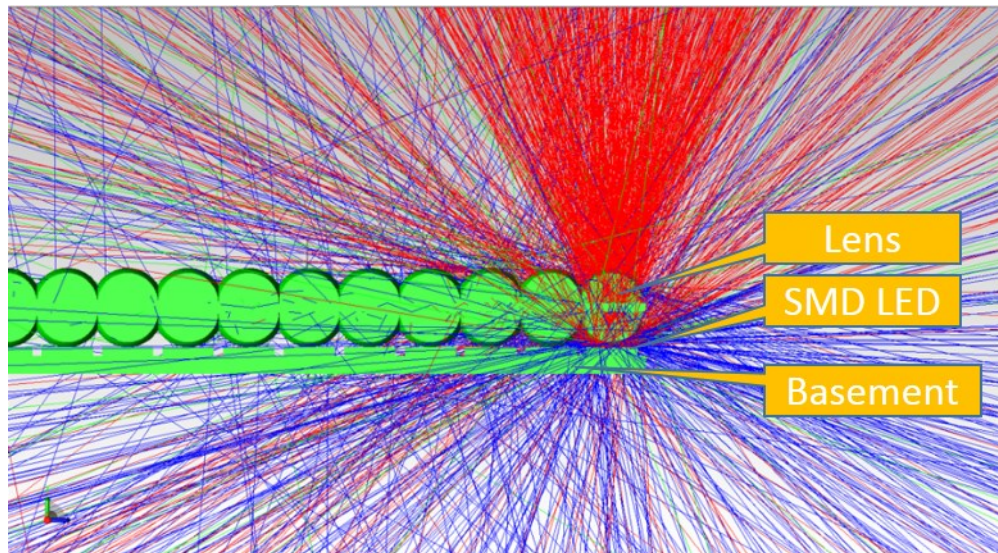


Fig 3. 2: Preliminary test result of a single SMD LED panel and lens array
The simulation result illustrates that even a strong lens array is unsuccessful to convert divergent light into collimated light.

Compared to the SMD LED, the emitting angle of approximately 15~60 degrees of the DIP LED is far behind that of the 120 degree of the SMD LED. Single DIP LEDs combined with lenses have been verified. Fig 3.3 shows the simulation result of a single DIP LED panel and a single lens on a lens array.

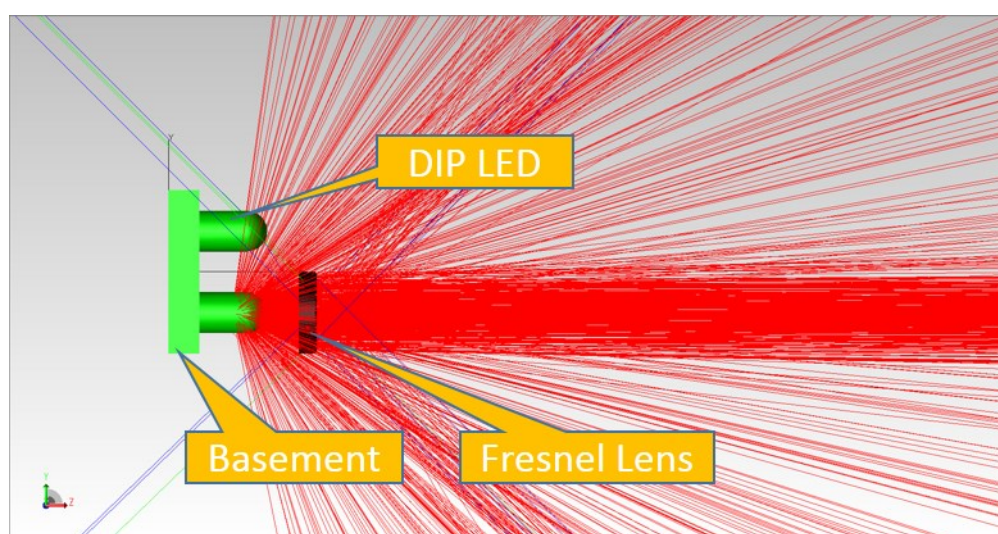


Fig 3. 3: Simulation result of single DIP LED panel and single lens on a lens array

Considering the shape of the distribution curve flux, this model is acceptable.

3.3 Simulation on multi-layers backlighting model

To verify the efficiency of the proposed system, we conduct an experiment using Tracepro software. We have conducted this experiment on a notebook PC with an Intel Core i7-4700MQ CPU (2.4 GHz), GTX 870M GPU (3 GB), and 16 GB of system memory. The operating system used in this experiment is Windows 8.1.

3.3.1 Unit of the DIP LED model

Fig 3.4 demonstrates the smallest unit and 3-layer units of the DIP LED model highlighted in the current research. The proposed model is composed of four DIP LEDs, four front-positioned parallel Fresnel lenses, which transfer divergent emitted light from the DIP LED into parallel light, as well as an achromatic convergent lens (right behind the Fresnel lens), which converges light, and a concave lens, which transfers the converged light into parallel light through a much smaller hole.

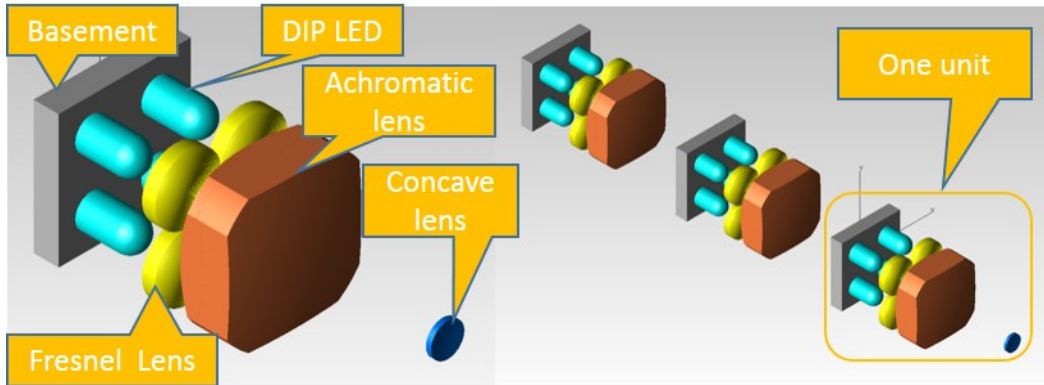


Fig 3. 4: One unit of the DIP LED model and 3-layer units

3.3.2 DIP LED Backlighting Model

Under consideration of final uniform illumination, the entire panel has been divided into many small units, with each unit encompassing 4 LEDs and independent lenses and holes. The size of one LED is $\varnothing 5$ mm, and one panel needs 560 LEDs. In the setting of the simulation, tracing rays of one LED have been set at 1000 pieces. The definitive model stacks 3 layers of units spatially. One panel adopts 14×10 units, which make it close to 14 in, as is shown in Fig 3.4.

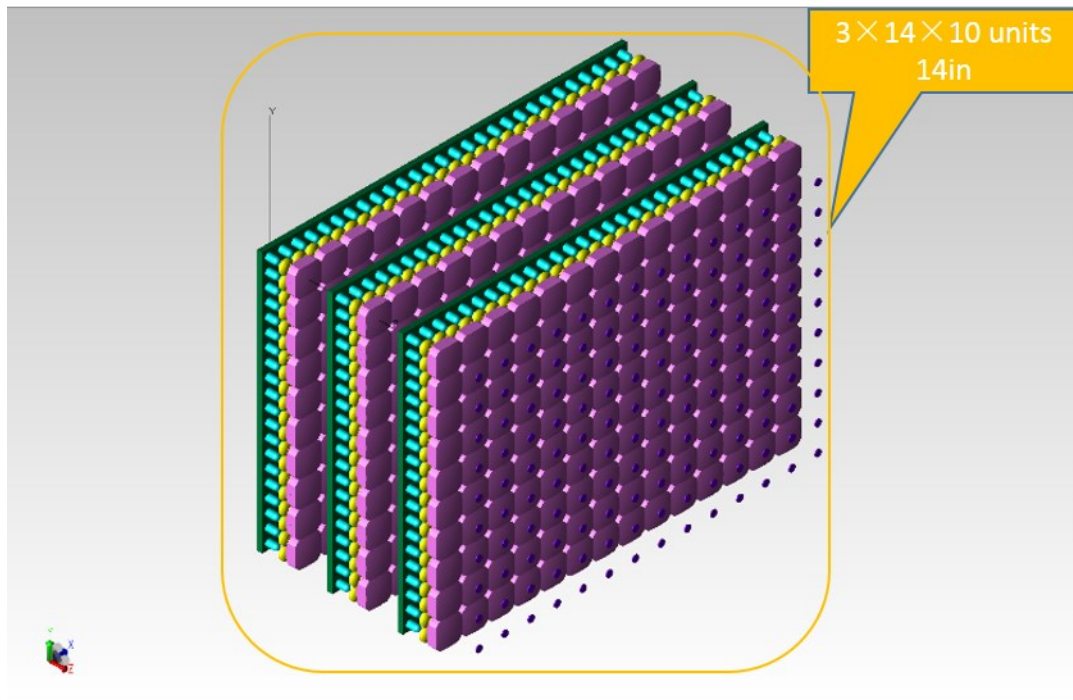


Fig 3. 5: DIP LED backlighting model with $3 \times 14 \times 10$ units

3.3.3 Illuminance of the DIP Simulation Model

Considering that a one-unit DIP LED emits overly concentrated light, four layers of the smallest unit are utilized in this paper as the basic simulation model to facilitate the analysis of the illuminance distribution and color distribution of space between units posterior to the formation of the backlight module.

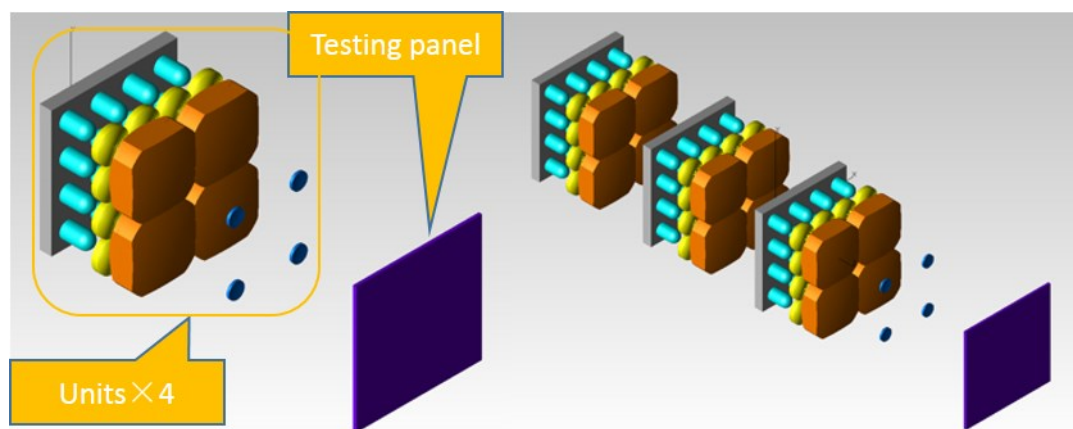


Fig 3. 4: Four units of the DIP LED model and a 3-layers unit

Tracepro has been employed to simulate the model shown in Fig 3.6 via the Monte

Carlo method of ray tracing. The adopted LED model uses a NSDW510GS-K1 DIP White LED produced by Nichia for reference. The surface source property generator of Tracepro gathers data from the light distribution curve and light spectrum distribution curve of the NSDW510GS-K1 DIP White LED and imports the data into Tracepro to determine the characteristics of the light source. The number of lights emitted from each LED is set as 1000, which then completes the core-parameter setup of LED lighting in this model. Furthermore, a testing panel is added to the front of the model, and the light absorption characteristics of the testing panel are defined. Then, energy analysis of the energy emitted to the LED panel is conducted using Tracepro. Fig 3.7 shows the simulation product of utilizing a single-layer backlight module. In the figure, the left energy distribution curve displays the distribution areas and evenness of high and low energy. The color bars, varying from blue, indicating low energy, to red, indicating high energy, are labeled by the Lux value - the illumination produced by luminous flux of one lumen falling perpendicularly on a one meter square surface. The numerical energy distribution curve on the right depicts the energy distribution within the testing panel. Judging from the left distribution curve, we can observe that the optical lenses are separated by gaps due to cutting round lenses into rectangular lenses, considering the overall structure of the model. Therefore, the center of the four lenses has reduced energy. A closer analysis of the right distribution curve shows that in each of the smallest original units, the center is home to the highest energy, and the energy is progressively decreases toward the margin because the energy emitted from the four LEDs overlaps in the center.

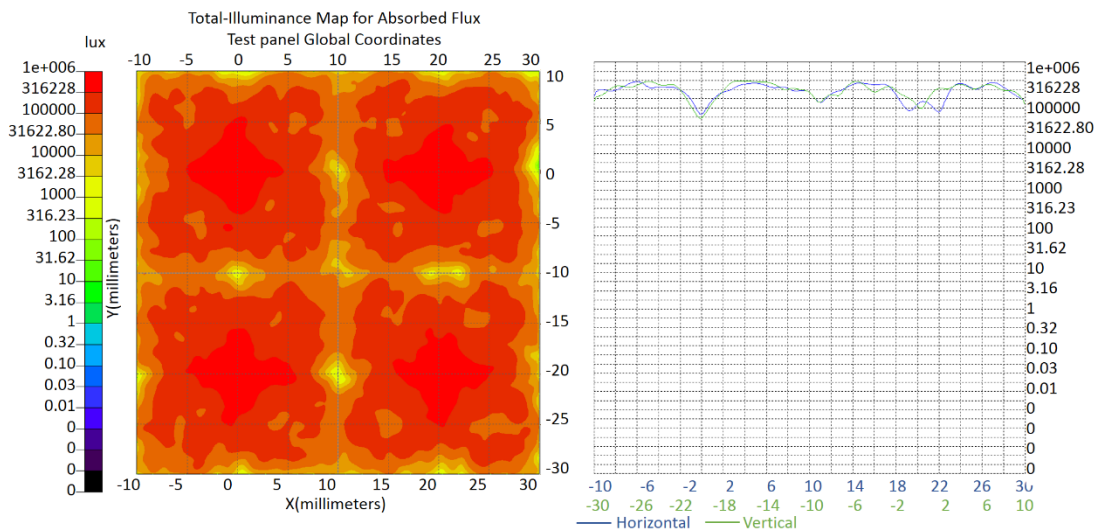


Fig 3. 5: Illuminance distribution of one unit under logarithmic treatment

The simulation of a three-layer backlight module is conducted in accordance with the right model in Fig 3.6 and the results in Fig 3.8. From Fig 3.8, we can readily see that under the same color value, the red color is darkened in the left, indicating the

increasingly intensified light energy as a result of the three-layer overlapping of the LED backlight module. The right distribution curve in Fig 3.8 demonstrates that the energy distribution is more even when stacking multiple layers of LED panels.

One unit is then expanded into three units. The purple small screen on the right side of Fig 3.6 is used to absorb the rays from 3 units of the LED panel.

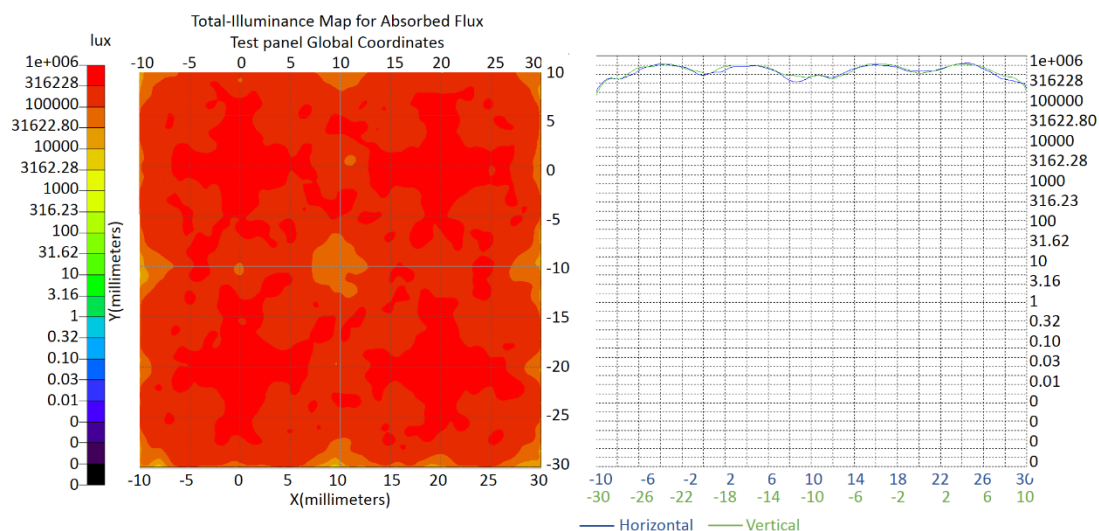


Fig 3. 6: Illuminance distribution of the 3-unit model under logarithmic treatment

The red color and color bar of Fig 3.7 and Fig 3.8 shown in the illuminance map illustrate the level of power. The curve on the right side of these two figures clarifies the accurate power distribution.

3.3.4 CIE Color Map Simulation

Color analysis constitutes a vital factor in the analysis of the backlight module, exerting direct influence on crucial parameters, including the color saturation level and the color temperature in the ultimate LED display. The NSDW510GS-K1 DIP White LED from Nichia is adopted as our structure model, and the parameters are imported to analyze the colors of the DIP LED using the u^*v^* color axes.

Colorimetry also plays an essential role in illuminance simulation. To increase the accuracy of simulation, the four-unit model has been tested in terms of color simulation.

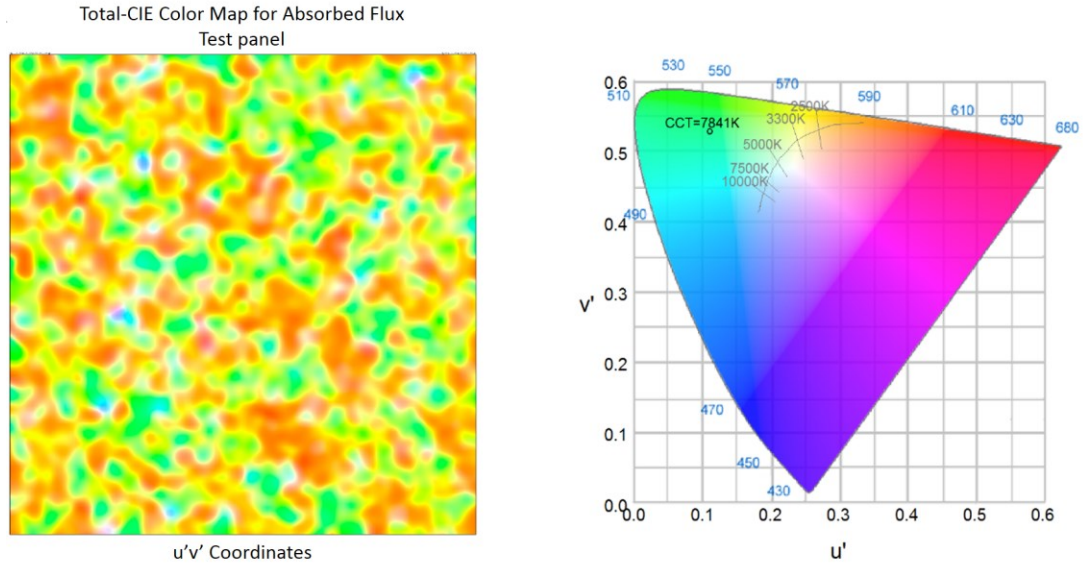


Fig 3. 7: Color distribution of one white DIP LED

Fig 3.9 shows the color distribution of one DIP LED. Although this DIP LED is a white LED, the color presented on the screen though the software is not pure white. Similar results have been obtained by other researchers [9].

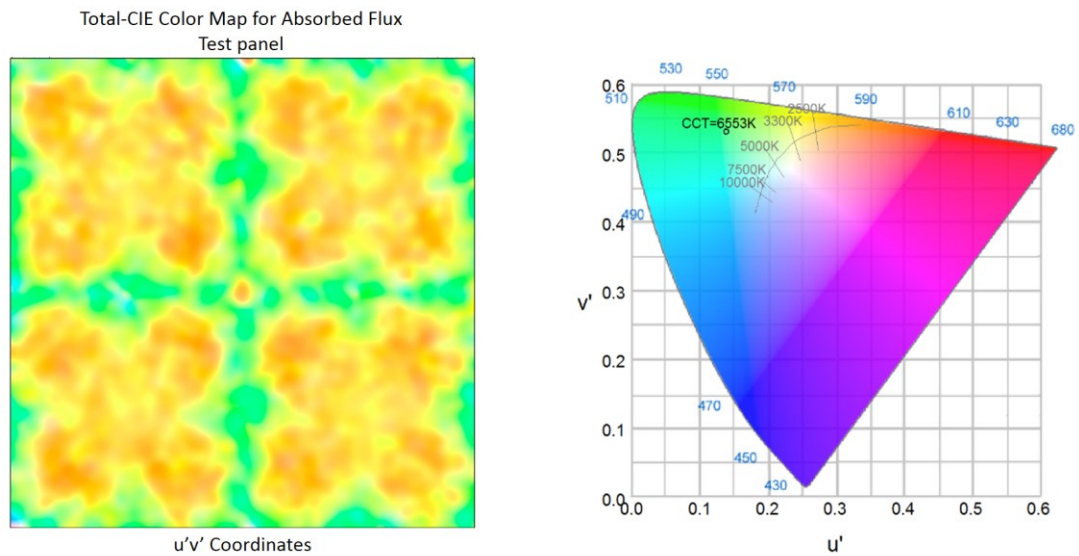


Fig 3. 8: Color distribution of the four-unit and one-layer model

Moreover, color simulation is conducted using four units of a single-layer module presented in the left of Fig 3.6. Judging from the simulation results, although the overall color is not pure white, its distribution evenness surpasses that of a single white LED. Similarly to the energy distribution, unevenness of the overall distribution caused by the space and margins of the model persists.

Because the white LED has a unique spectral distribution, the color distribution is not entirely white in the simulation of the software. However, Fig 3.10 shows a better effect than Fig 3.9 with respect to color distribution.

3.3.5 Energy Efficiency of the Three-Layer DIP LED Backlighting System and One Dense Layer SMD Backlighting System

For original LCD displays, the illuminance of a one-layer SMD LED backlight suffices. The distribution of SMD LEDs is loose. Amplifying the illuminance by 2 or 3 times increases the density of the distribution. Considering the size of a circuit board and the thermal effect, the approach of increasing the density of SMD LEDs has limited effect and is unreliable. However, by means of the evaluation software of the performance of stacked DIP LED backlighting systems, the increased density of an SMD LED backlighting system is simulated.

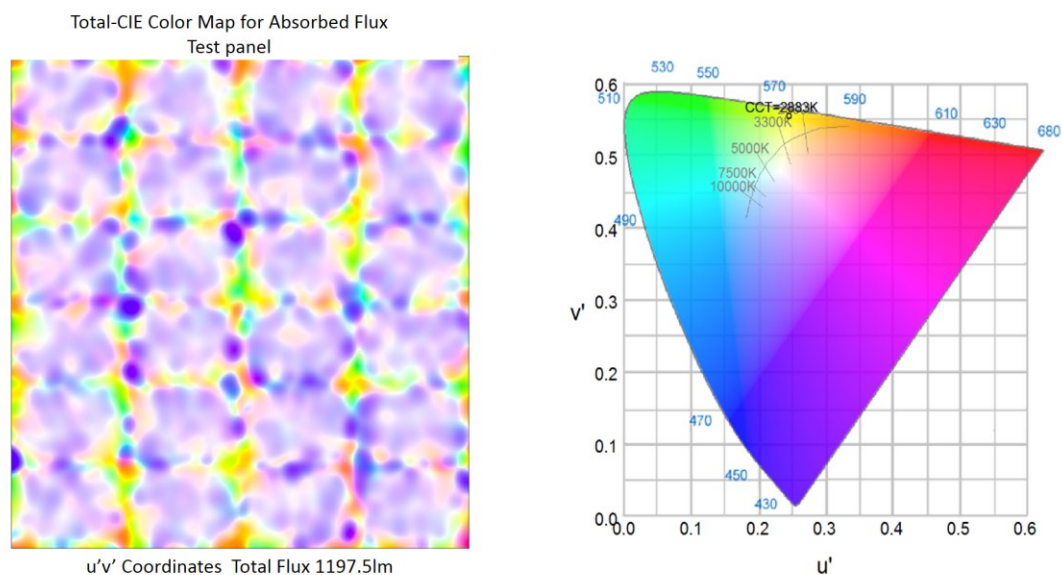


Fig 3. 9: Color distribution of one-layer SMD LED backlight

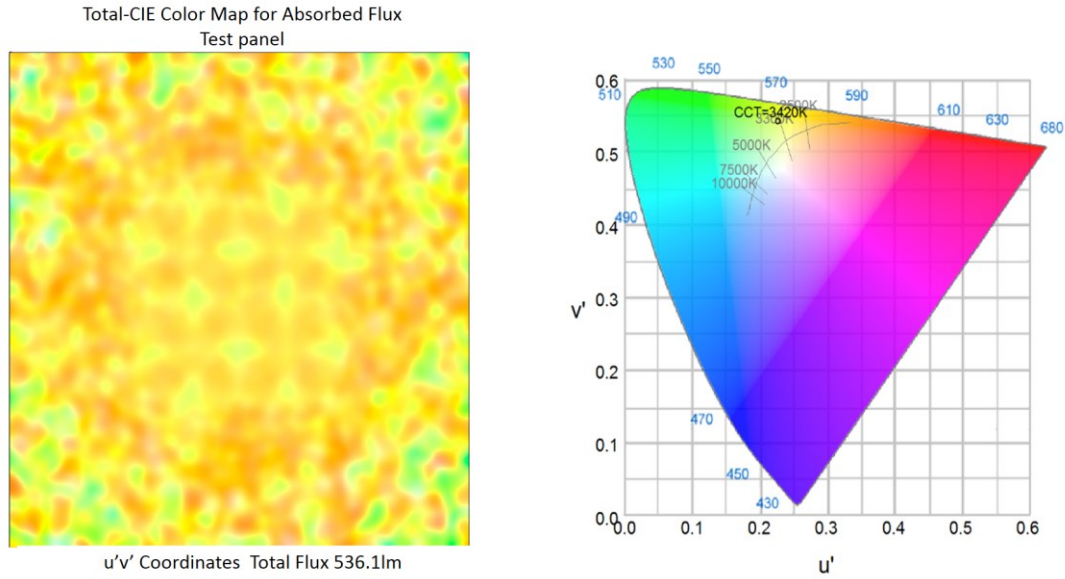


Fig 3. 10: Color distribution of three-layer DIP LED backlight

Fig 3.11 and Fig 3.12 show a 12 W difference of the color distribution and different illuminance under the same power. Fig 3.11 demonstrates the illuminance of an SMD LED reaching 1197.5 lm, whereas Fig 3.12 illustrates the illuminance of the three-layer DIP LED reaching 536.1 lm.

This simulation result is obtained under the same conditions, the same size of absorption screen and without cover of the backlighting system. However, the construction of these two types of backlighting systems is different, giving rise to different test results. Another test shows if the size of the absorption screen is increased and the reflective cover of the backlighting system is given, the SMD backlighting system stays the same but the DIP backlighting system is increased to 700 lm.

3.4 Analysis and Discussion

3.4.1 Analysis of Energy Degradation

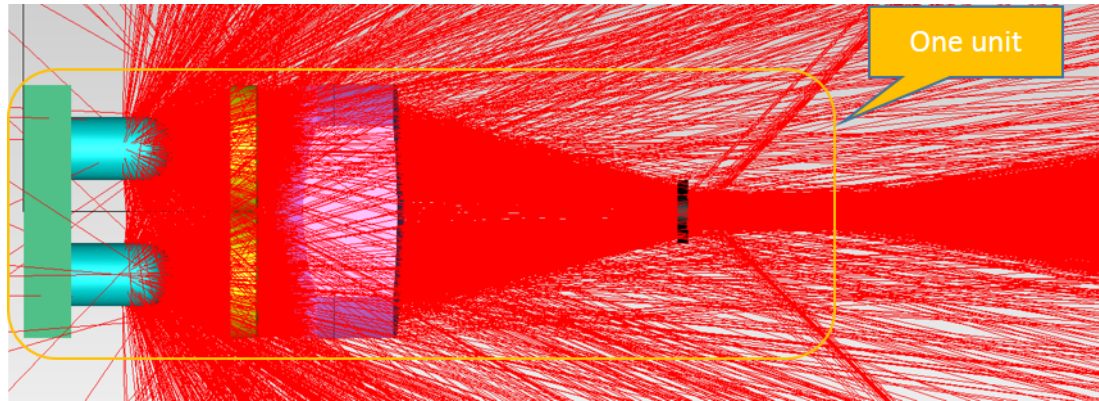


Fig 3. 11: Trace performance of real rays

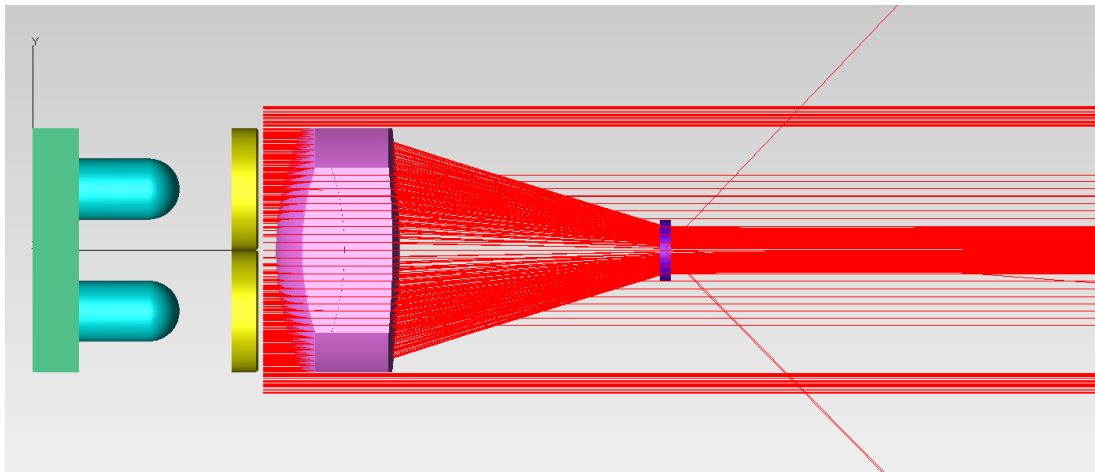


Fig 3. 12: Trace performance of hypothetical perfectly collimated light rays

Fig 3.13 shows the test result of the one-unit irradiance model. The rays from the four DIP LEDs on the panel with a 35 degree emitting angle pass through 4 Fresnel lenses and a lens group. This result directly shows why the energy degradation is so large. In addition, it also shows that the lost energy is coming from the large amount of missing rays.

To analyze the cause of the large amount of missing rays, we attempted to shut down the emitting part of LED and use a standardized grid light source to emit a group of perfectly collimated light to test the performance of the lens group. The result proves that the design of the lens group is correct.

By comparing these two figures, it is obvious that the 35 degree emitting angle from LED produces a large amount of missing rays from the concave lens and can maintain collimated light for only a short distance. How to design the lens or redesign the lens array remains a challenging issue.

3.4.2 Analysis of the Illumination Uniformity

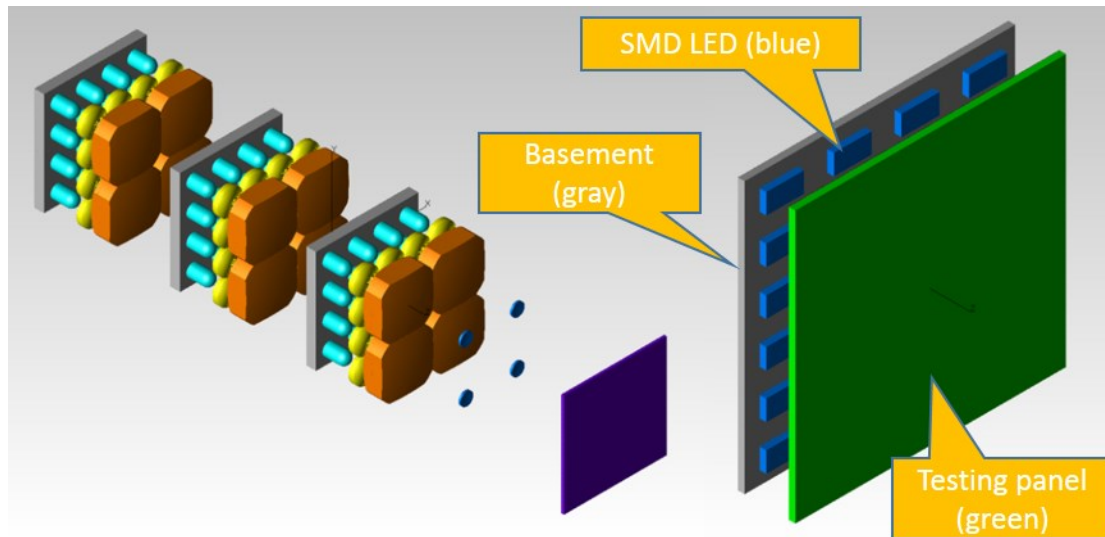


Fig 3. 13: Comparison between the model of the three-layer DIP LED backlighting system and the single-layer SMD backlighting system

We use the software to simulate a simplified model of a small array of a three-layer DIP LED backlighting system, as shown in Fig 3.15 (left). The structure of the current most widely used conventional SMD backlighting system model is presented in Fig 3.15 (right). Then, we compare the distribution of the illumination uniformity.

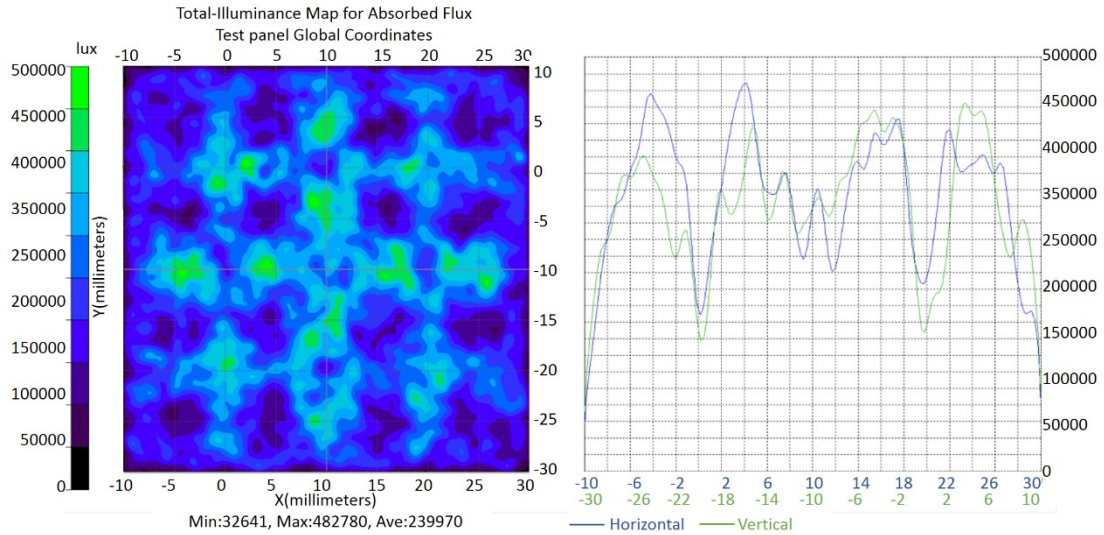


Fig 3. 14: Illumination distribution of the three-layer DIP LED backlighting system

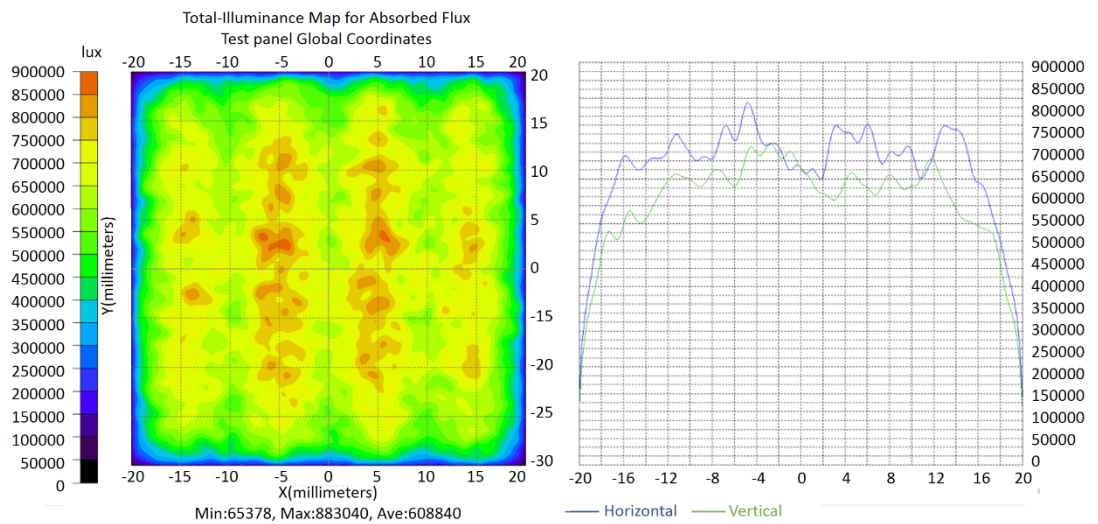


Fig 3. 15: Illumination distribution of the traditional single-layer SMD backlighting system

The green and blue curves showed vertical and horizontal illumination distribution of the left map both it the Fig 3.16 and Fig 3.17. Considering the structure of the emitting model, the traditional single-layer backlighting system contains a white light SMD LED lamp with a light emitting angle of 120 degrees, which the most commonly used in recent displays cannot be used in the new system. However, the three-layer DIP LED backlighting system using the white light DIP LED with a light emitting angle of approximately 35 degrees can be used in this spatial stacked backlighting system.

The illumination uniformity is calculated by the minimum value of the light field

illumination divided by the average value. In the process of simulation, the software automatically calculates the minimum, the maximum, and the average value of the entire light field illumination. As a result, the illumination uniformity of the three-layer DIP LED backlighting system is 9.5%, as shown in Fig 3.16. The illumination uniformity of the traditional single layer SMD backlighting system is 10.7%, as shown in Fig 3.17. Although we can see the illumination distribution in Fig 3.16 is not as good as the one in Fig 3.17 with respect to the illumination uniformity, the calculated results are similar, which proves the reliability of the illumination uniformity of the spatial-enhanced backlighting systems.

3.4.3 Color evaluation of the three-layer DIP LED backlighting system and the conventional single-layer SMD backlighting system

According to the model in Fig 3.15, through the simulation, the analysis result on the color distribution after the simulation is shown in Fig 3.18 and Fig 3.19.

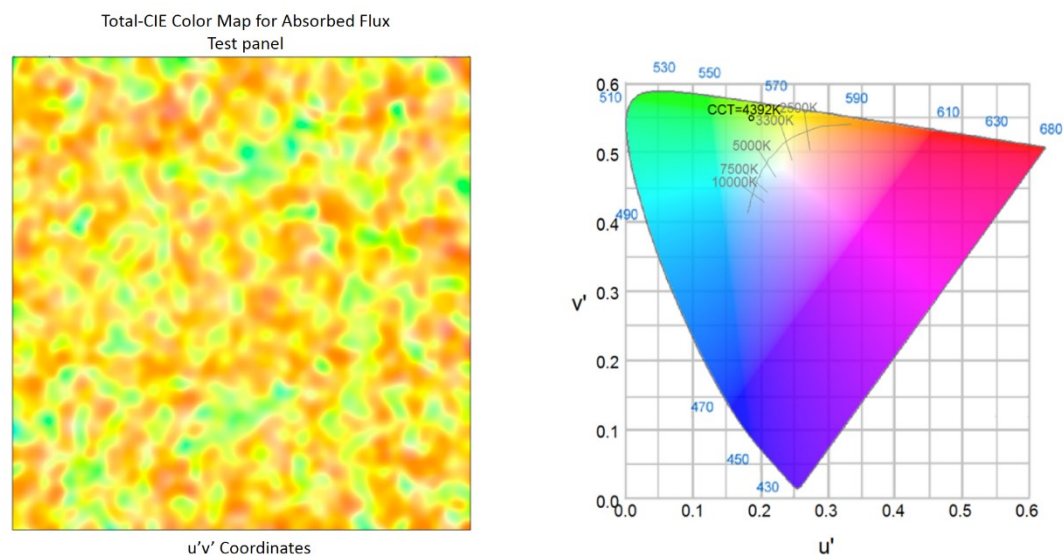


Fig 3. 16: Color distribution of the three-layer DIP LED backlighting system

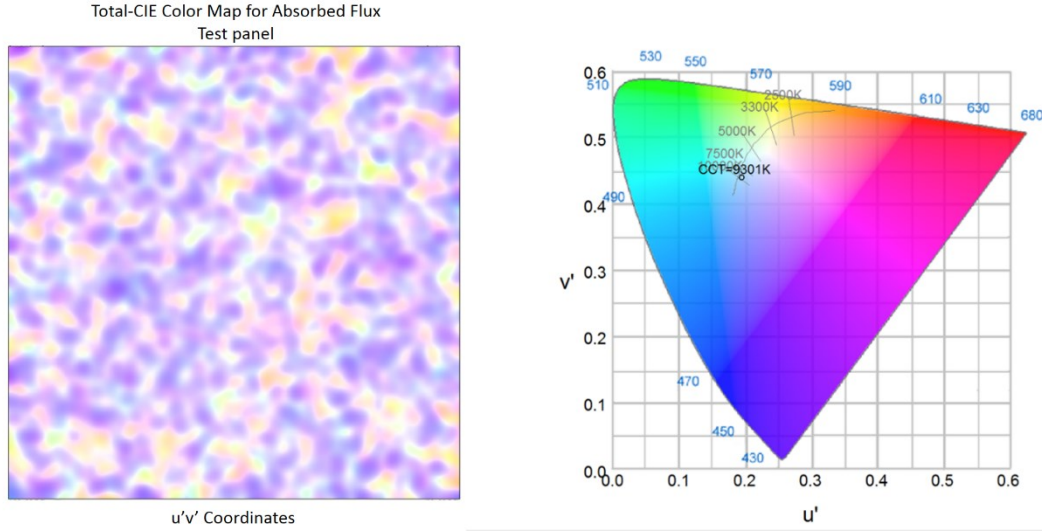


Fig 3. 17: Color distribution of the traditional single-layer SMD backlighting systems

From Fig 3.18 and Fig 3.19, we can see the color distribution on the simulated LCD surface is quite different, even when using a similar white light spectral distribution of the LED. We use software to export the color coordinates (u, v) of the color distribution, and the CIE-related color difference formula is used to calculate the color difference of the two models.

The color difference between the colors coordinates u_k, v_k of the testing light sources and the color coordinates u_r, v_r of the reference lighting body is presented as (1).

$$\Delta C = [(u_k - u_r)^2 + (v_k - v_r)^2]^{\frac{1}{2}} \quad (1)$$

The color temperature of the LED lighting is usually the closest to the standard D65 light source, and the D65 color spectrum also represents the average solar spectrum color. Therefore, we choose the D65 light source for the color coordinates ($u = 0.1978, v = 0.3122$) in the CIE1960USC (CIE 1960 UCS, variously expanded Uniform Color Space, Uniform Color Scale, Uniform Chromaticity Scale, Uniform Chromaticity Space) is another name for the (u, v) chromaticity space devised by David MacAdam) chromaticity diagram.

We export the color coordinate data of the enhanced backlighting systems and use the color difference formula to calculate the color difference ($\Delta C_{av1} \approx 0.2320$). Then, the color coordinates of the traditional backlight systems are imported, and the average value of the color difference ($\Delta C_{av2} \approx 0.1254$) is calculated. Because the spectrum and the color temperature of the white LED light source are different from the standard reference illuminant D65, there is a deviation, so a color difference exists within a

reasonable range. Due to some factors adopted in the enhanced light source structure that influence the spectra, such as the lens, the color deviation is greater than the one of the traditional backlight system.

3.5 Limitation

One major problem is the thermal analysis. As seen from Fig 3.4, the final model uses a large a device that is 14 in in width and 3 layers in depth. This structure would accumulate heat, resulting in breaking of the lens and an effect on the LED [10]. Heat can reduce the durability of LEDs. In following work, we will not only analyze the power efficiency but also discuss the thermal solution; otherwise, the lens will break or reduce the durability of the LED [11].

3.6 Future Work

In our future work, we will apply this model to practice and test the efficiency in the real world. It is our sincere hope that there will be more exploratory research into the recently emergent backlight sources, such as the laser backlight source, which has already been utilized as the main light source in projectors and a small number of newly designed LED television sets. The laser backlight source has the virtue of durability and stability similar to LEDs because they both belong to solid light sources. However, compared with LEDs, the laser backlight source is much more advantageous in that its smaller size and greater luminance contribute to its relatively mature application in marketized projectors. Furthermore, because a laser is a collimated light source with a small angle of divergence, the ideal effect demonstrated in Fig 3.14 can be readily achieved to greatly lessen the energy loss if a laser is utilized in the model proposed in the current research. Moreover, taking into consideration the high luminance of the laser itself, we can safely predict that the backlight luminance provided by the ultimate structure will be increased significantly.

On the other hand, the increasing popularity of the LED backlight in everyday devices, such as computer screens, LED television sets and smart phones, has brought into the spotlight the resultant health issues, especially blue light-reducing. In view of multiple factors, including cost and efficiency, an overwhelming majority of LED screen devices adopt single-core, white-light LEDs instead of RGB three-core LEDs whose application is limited to a small number of professional fields with high demands on

color effects. Therefore, the influence of white-light LEDs on users' health is a primary concern. Recent research showed that energy from blue-light surpasses that from any other light because single-core white-light LEDs originate from yellow fluorescent powder generated by blue light. Moreover, due to its shorter wavelength and higher frequency, blue light exerts higher energy compared with longer wavelength red and green lights. If the wavelength is further reduced, the blue light wave band will then become ultraviolet wave band, which is widely known as extremely detrimental to living organisms, especially cells, and is thus extensively applied in sterilization. Therefore, single-core LEDs with high-energy blue light wave bands are exerting multifaceted influence on users' health, resulting in direct disastrous consequences, including compromising users' eyesight because long exposure to high-energy blue light damages visual cells. Additionally, the latest research reveals that blue light also has a negative impact on hormone secretion of the human body, human energy and sleep. Some primitive methods have been devised to eliminate blue light, such as adding optical filters or simple filter glasses to LED screen devices to filter some blue light energy. Nevertheless, these approaches, while aiming to filter blue light, lead to distortion of the overall white light. Thus, the current model is proposed to explore how to reduce blue light without distorting the overall color performance. The simulation results of Fig 3.11 and Fig 3.12 indicate that the added lens in the backlight modules in Fig 3.11 enables the partial filtering of blue light. Therefore, although both use single-core white-light LEDs, Fig 3.11 and Fig 3.12 differ in color performance in their ultimate simulation. What remains as our future concern is the quantifiable analysis of the degree of blue light reduction and revolutionized structure and design of blue light reduction models.

3.7 Result

In this paper, we proposed a high-luminance, spatial multiple-layer, LED backlighting system. We created the model using a hole in the LED panels and lens to make the light radiate from the rear panel to the front panel by multiplying the power of radiation. A high light output was achieved. The whole model was simulated and tested by the optical software Tracepro, which can use the Monte Carlo ray tracing technique to describe the route of the rays. Upon the completion of computing transparent and missing rays, the illuminance maps were also simulated to evaluate the light distribution. From the experimental results, we can see that the proposed system is efficient to provide a high output light source to meet many requirements.

Chapter 4 Simulation of human centered back-lighting system using two types of LEDs

4.1 Background

Nowadays, Liquid Crystal Display (LCD) system has permeated among every aspect of our daily lives. However, few people know the blue light hazard of Light Emitting Diode (LED), which is widely used for light source in backlight system of display device. Presently, many manufactures take a series of countermeasures on it. Most countermeasures focuses on reducing blue light through software technology since it is easily to actualize and almost no cost. However, there still have two manufactures insist on hardware method to reduce the blue light hazard which considering maintain the color performance. In this paper, we have propose a new method of reducing blue light via hardware and have evaluated both their methods by software and hardware by numerical analysis. . The new design is based on a backlight system in which the original white LED is modified so that the blue-band energy is reduced by 50% and the cyan light LEDs are added among the white light LEDs. Then, we have optimized and adjusted the distribution of LED's energy in order to reduce the harm of the blue light, and have maintained the good color performance at the same time. According to the simulation result, the newly designed backlight unit could effectively cut down over 50% blue light and kept the correlated color temperature (CCT) in 6081K which approaches the standard value 6500K. Besides that, the color rendering index (CRI) can also keep at 74.818 which is almost as same as ordinary white LED without blue light filtering.

Liquid crystal display (LCD) device has become the most commercially successful panel display device. It is widely used in mobile display terminals, home entertainment and commercial exhibition. However, the liquid crystal is none-luminous, and the LCD backlight system is required to flash LCD panel. Moreover, Light Emitting Diode (LED) become the best choice of backlight system. First of all, due to the features of solid light sources, which have a long life, high brightness, low power consumption and etc. In addition, LED has been the price down to the same price of traditional light source with the popularity of LED technology and the mass production.

However, the blue light hazards is pointed out as one of the most serious problems of LED in many published papers such as Understanding Radiation Safety of High-Intensity LED [14]. These studies shows that the vision is the most important feeling to human, over 80% of information is obtained from the vision for humankind. Therefore, the potential danger of blue LED is one of the focus point in the field of biological safety in recent years.

To remove the blue light hazards, software technologies have been developed to modify an original image which includes a blue light component. In addition to the software technologies, the hardware technologies which employ a specialized attachment on the screen, have been developed. They can remove the blue hazard to some extent, however, the CCT still significantly below normal levels. The color rendition of them are still restricted by spectrum of traditional white LED. To solve the problem, we have proposed a new method based on the adjustment of spectrum by adding cyan LED. Cyan LED plays a vital role in arising the CCT and proving the CRI

Besides that, an important research work has been presented that human melanopsin forms a pigment maximally sensitive to blue light ($\lambda_{\max} \approx 479$ nm) supporting activation of $G_{q/11}$ and $G_{i/o}$ signaling cascades [15], and the 479nm is the wavelength of cyan. In addition, as another research work, the sleep pattern and circadian rhythms are regulated via the retinohypothalamic tract in response to stimulation of a subset of retinal ganglion cells, predominantly by blue light (450-490 nm) has been shown [16], and this band of wavelength is also blue and cyan. Therefore, to reduce all of the component of blue light is not all good.

4.2 Analysis on traditional method of blocking blue light hazard

The two methods of blocking blue light hazard has been mentioned at related works, by software and hardware. Software method though changing the standard of RGB color space to cut the blue light when hardware method though adjusting the hardware of black light panel, like using filter to LED or changing the phosphor of LED to cut the blue light. However, the better way to make a choice some display system with the function of blocking blue light hazard for some average customers is not known exactly how. Moreover, how the color performance and the blue light blocking is effect on the

color performance is unclear. In this paper, we provide the basis for the judgment of the average consumers through the evaluation of these methods which by visual analytics.

4.2.1 Establish the standard model of common LCD backlight system

To evaluate the effect of two method of blocking blue light hazard, we have developed a standard model which without processing. This model can be also used in following works just need to adjust some parameters and modified. By means of parameter settings and calculations, we can get Total Illuminance Map and Total CIE Color Map.

CCT is a physical quantity used to define the color of the light source in illumination optics. The color of the light source is often represented by CCT. Currently, on the market the vast majority of ordinary liquid crystal displays used are with the CCT between about 6000-6500K white LED and 6500K is the standard light source D65 CCT. Therefore, the use of this CCT of the display is currently the vast majority.

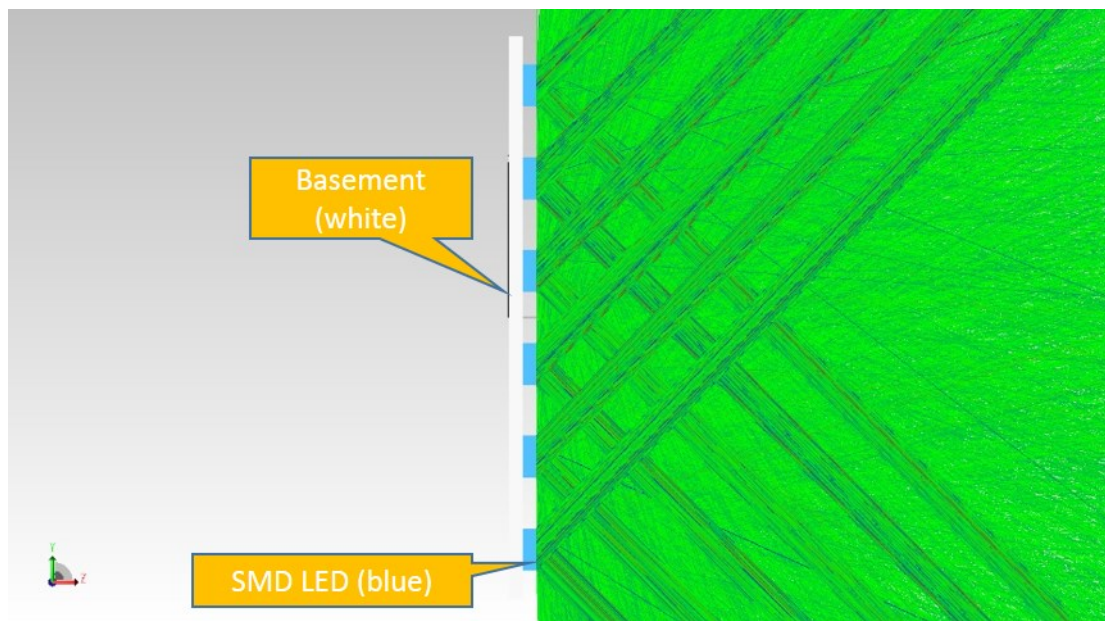


Fig 4. 1: Simulation of ordinary LCD backlight LED by ray tracing

Fig 4.1 shows a simulation results with Monte Carlo method by using a large number of ray tracing on the backlight LED. This method has been tested very useful in the precise optical modeling of blue LED [17].

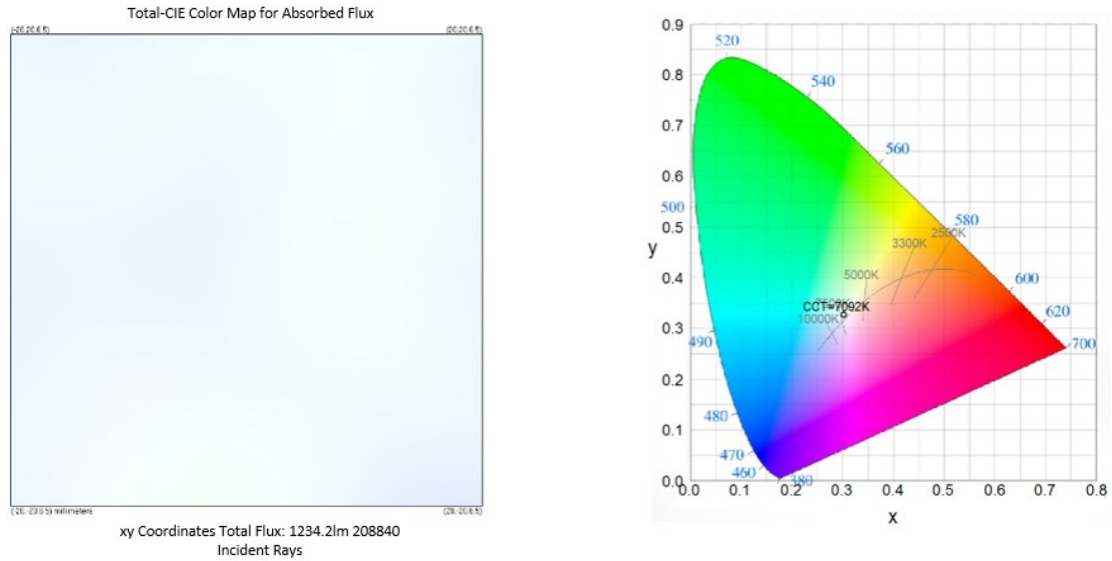


Fig 4. 2: The total CIE Color Map of general LCD display backlight LED after simulation

Fig 4.2 shows the Total CIE Color Map of the calculation results by ray tracing. The left in Fig 4. 2 shows the light source of backlight after the light presented by the spectral color. The color is almost cold white, and the light field distribution is basically uniform. The coordinates of the right graph are the standard CIE 1931 color coordinates, in that the light field distribution is basically uniform, but not completely uniform. Therefore, there will be a slight deviation in the simulation of the color coordinates. The backlight spectral CCT is about 7000K is marked in Fig 4.2. It is the average value of the entire light field.

In the progress of backlight LED parameter settings, we use the spectral distribution data of Samsung 5630 lamp beads under 6500K but the actual simulation results are slightly higher than the 6500K. Taking various factors into account such as the arrangement density of the LEDs in the modeling and the stray light produced by the Monte Carlo pursuit, the simulation results are within the error range.

4.2.2 Modeling and analysis of blue light filter through software

At present, according to user needs, the blue screen of the software manufacturers provides three ways to filter blue light of 30%, 50% or 70%. As the increase of proportion of blue light filtered through the software, the color cast of display will be more serious. So, the user will commonly choose 30% or 50% blue light filter mode. Here we analyze the effect of three kinds of filtering blue light through the simulation results of the model.

Figures 4.3-4.5 show the color performance of LED backlight module after the light source have filtered the blue light of the percentage of 30%, 50% and 70%. From these results, we found that the higher the proportion of blue light is filtered, the more the original white backlight color shifts to the green. It also results in a severe distortion of the final display color.

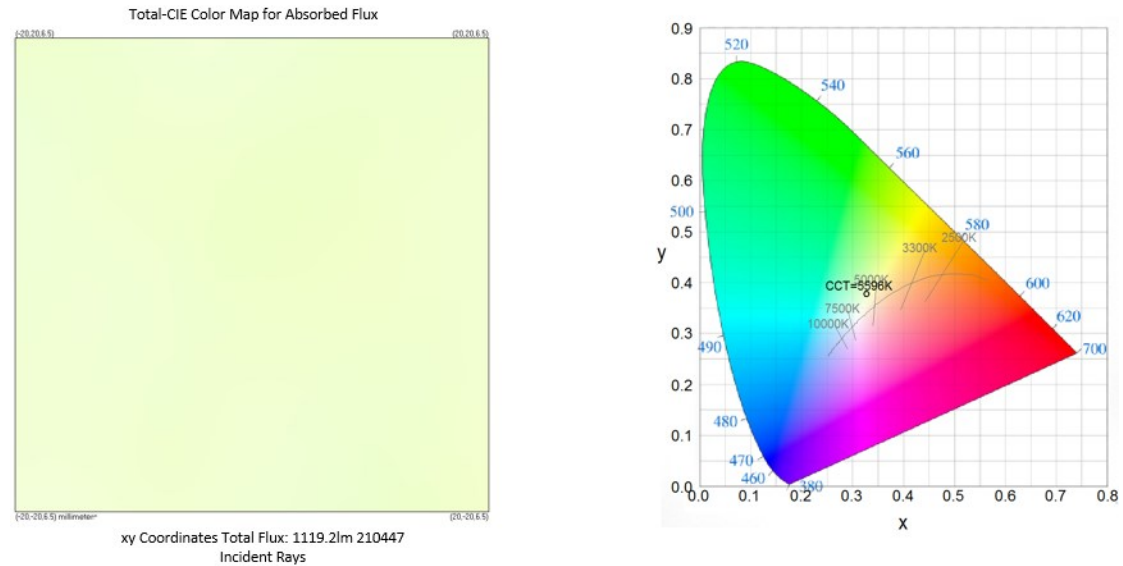


Fig 4. 3: Total CIE Color Map of ordinary liquid crystal display obtained after filtering 30% blue light

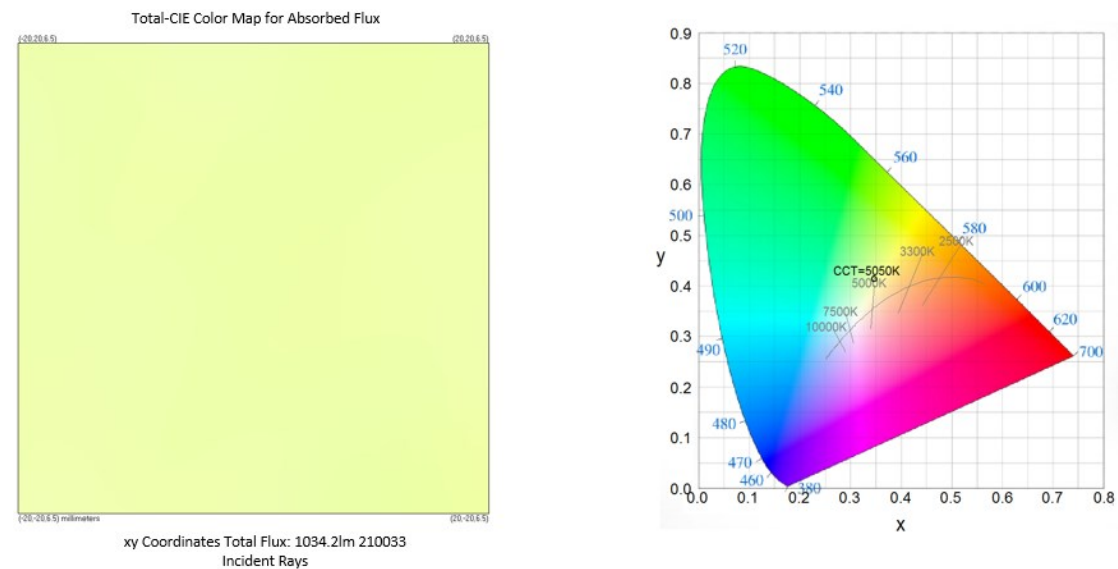


Fig 4. 4: Total CIE Color Map of ordinary liquid crystal display obtained after filtering 50% blue light

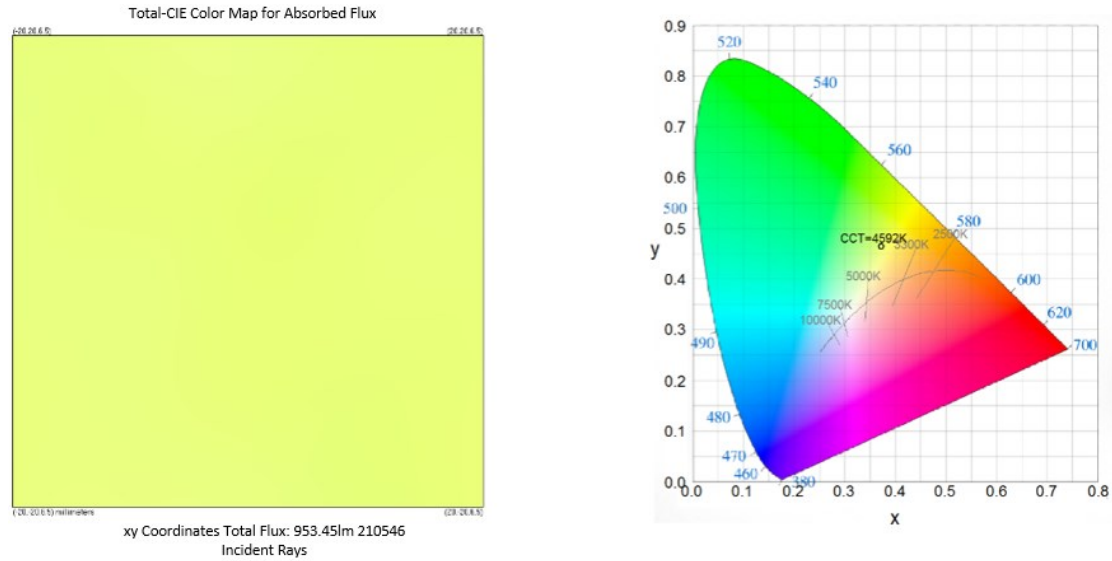


Fig 4. 5: Total CIE Color Map of ordinary liquid crystal display obtained after filtering 70% blue light

From the comparison of the parameters in Table 1, we have clarified that the more the blue light filtered, the more the CCT decreases and the CRI along with the luminous flux of the whole output will decrease at the same time.

Table 4. 1: Comparison of optical characteristics of different ratios of blue filters

Blue light filtering	CIExy	CCT(K)	RGB	CRI	Total Flux (lm)
30%	(0.37, 0.46)	5618	(227, 255, 169)	69.6	1034.20
50%	(0.33, 0.37)	5029	(222, 255, 111)	67.6	973.79
70%	(0.35, 0.46)	4623	(221, 255, 55)	63.8	953.45

However, few people is acceptable this color performance of display device, even though it is healthy for human's eyes. Except the existence of free software of blue light filtering and accessory function via software filtering which be provided by manufactures, the new blue light filtering method in software, like using colorimetric characterization of the display [18] have been developed. However, they are still insufficient especially in CRI.

Two hardware methods by AOC and BenQ to improve software method have proposed, even they cost much more and make backlight system become more complicated. However, is that really the performance of these two methods are better than software and also be work for filtering blue light hazard If not, weather we need a better proposal for filtering blue light hazard.

4.2.3 The mechanism of filtering blue light hazard by hardware

According to the analysis and description of the related work, we have developed the model of backlight panels of AOC and BenQ as shown in Fig 4.6. The model is given the corresponding material properties and optical parameters of the backlight model. According to the technical information published by BenQ, the blue light filtering method is to cutting down wavelength below 455nm. However, the specific percentage to cut has not been revealed. In terms of the bad effect of blue light on health, we use blue light completely below 455nm as the basis of simulation, and then evaluates and compares them.

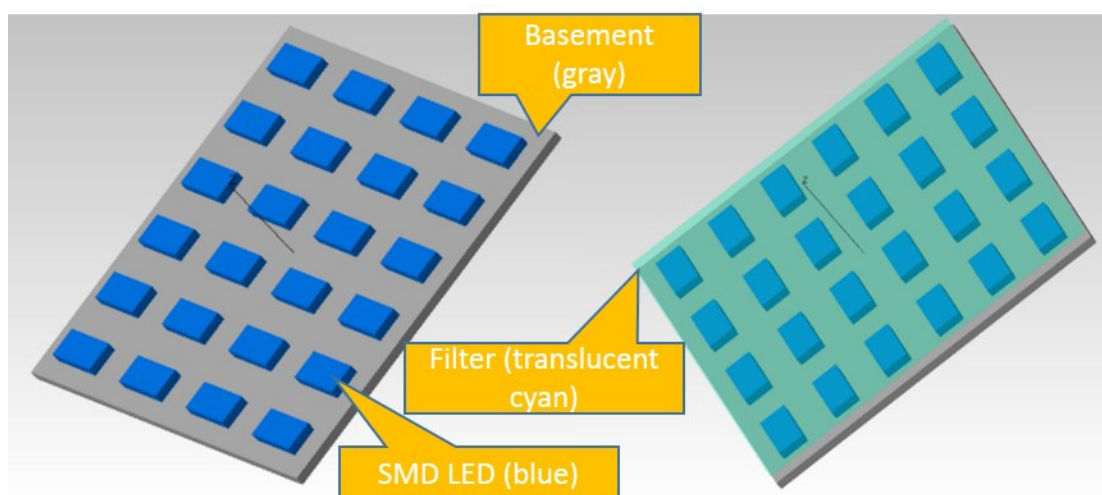
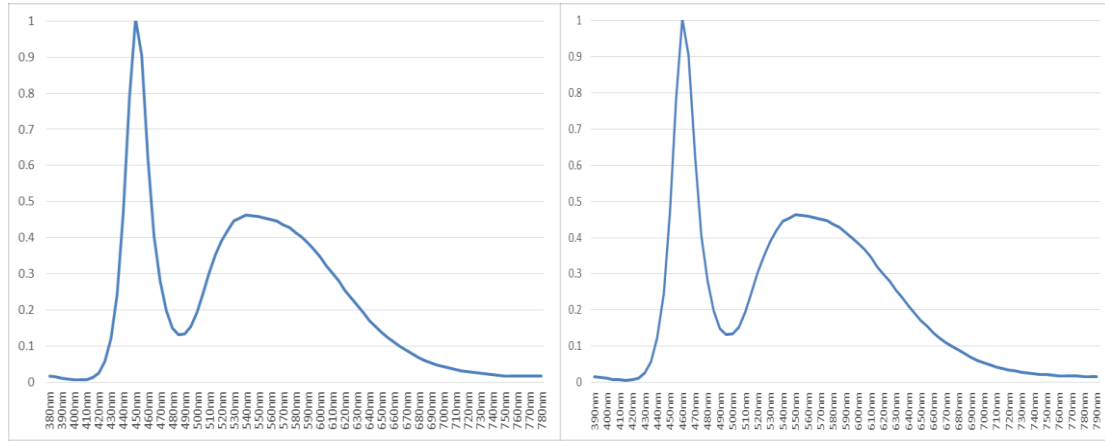


Fig 4. 6: The backlight model of AOC and BenQ

Fig 4.7 shows the backlight LED spectral distribution of common liquid crystal display and AOC and BenQ. Fig 4.7 (a) shows the spectral distribution curve of ordinary white LED, which is the most widely used blue light LED. The abscissa is the wavelength of visible light from 380 nm to 780 nm, and the ordinate is the normalized energy distribution. It is clear from (a) that although the wavelength broadening of blue light is only 100 nm from 380 nm to about 480 nm. The proportion of the energy of the blue part is quite high, especially in the wavelength of 440-450nm, even though the entire range of visible light is from 380 nm to 780 nm. Therefore, many studies have shown that this part of the high-energy blue light is harmful to the physical health especially the human eyes.

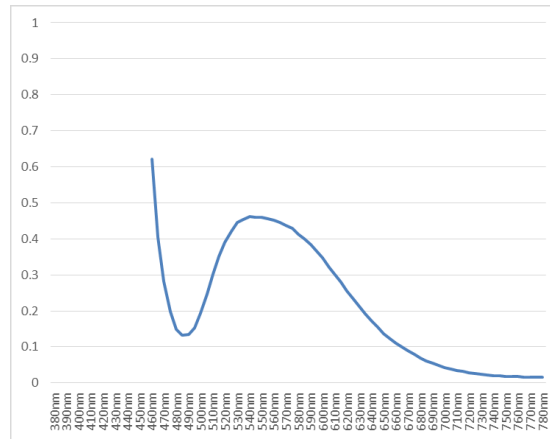
The spectral distribution curve of the backlight LED in Fig 4.7 (b) and (c) is obtained from AOC and BenQ after adjusting the ordinary white LED based on the above

principle. From the comparison of (a), (b) and (c), we have clarified that (b) adjusted little from (a) that only the whole spectrum shifted 10 nm towards the right direction. They moved the most harmful peak wavelength of blue light. On the other hand, the spectrum in Fig 4.7 (c) changed a lot. The spectrum distribution of BenQ cut down the blue light below 455nm completely, as it concerned that the wavelength under 455nm is the band of blue light hazard. Because of these different improvements and changes, they change the optical properties and parameters, such as CCT and CRI.



(a) Ordinary white LED spectrum distribution

(b) Backlighting LED spectrum distribution of AOC display



(c) Backlighting LED spectrum distribution of BenQ display

Fig 4. 7: Backlighting LEDs spectrum distribution for common LCD displays, and for AOC and BenQ displays

4.2.4 Simulation results and analysis of two kinds of blue light filtering display backlight

Figures 4.8 and 4.9 show the backlight color simulation results of two companies AOC and BenQ applying hardware methods of filtering blue light to LCD. The simulation results of AOC (Fig 4.8) shows that the CCT of the backlight source is warmer than that of the normal white light because it shifts the blue wavelength band and does the processing of cutting down the blue light. Therefore, the CCT is reduced from about 6500K to about 5800K, which is not serious degraded. The simulation result of BenQ's blue light display backlight show that the backlight color has a severe deviation from the normal cold white light because it completely filters out the blue light below wavelength of 455nm, the color cast is also more serious. CCT decreases from the ordinary backlight of about 6500K to about 4900K.

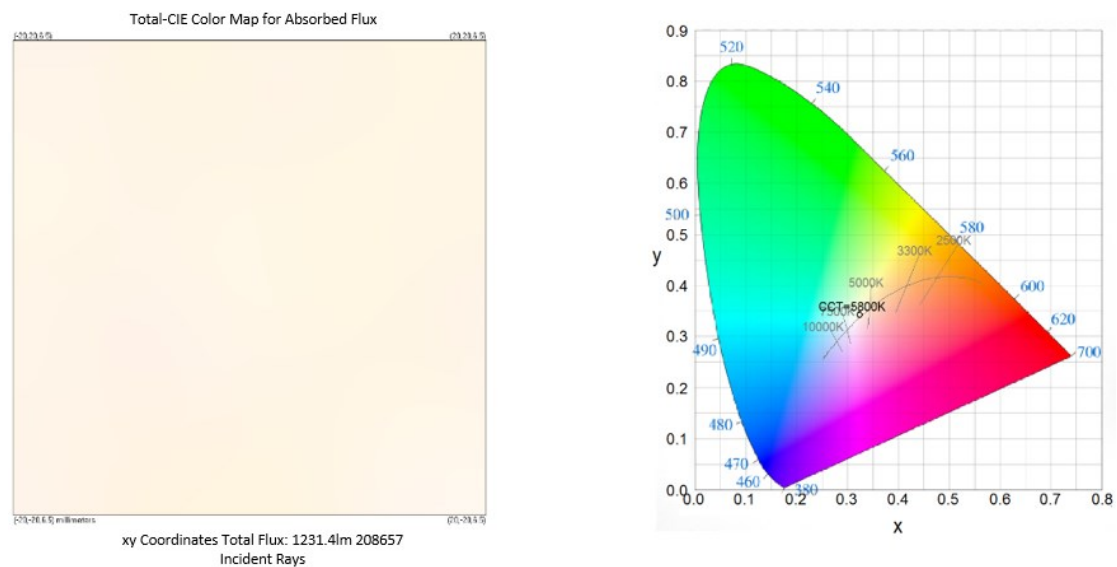


Fig 4. 8: The total CIE Color Map of AOC liquid crystal display backlight LED after simulation

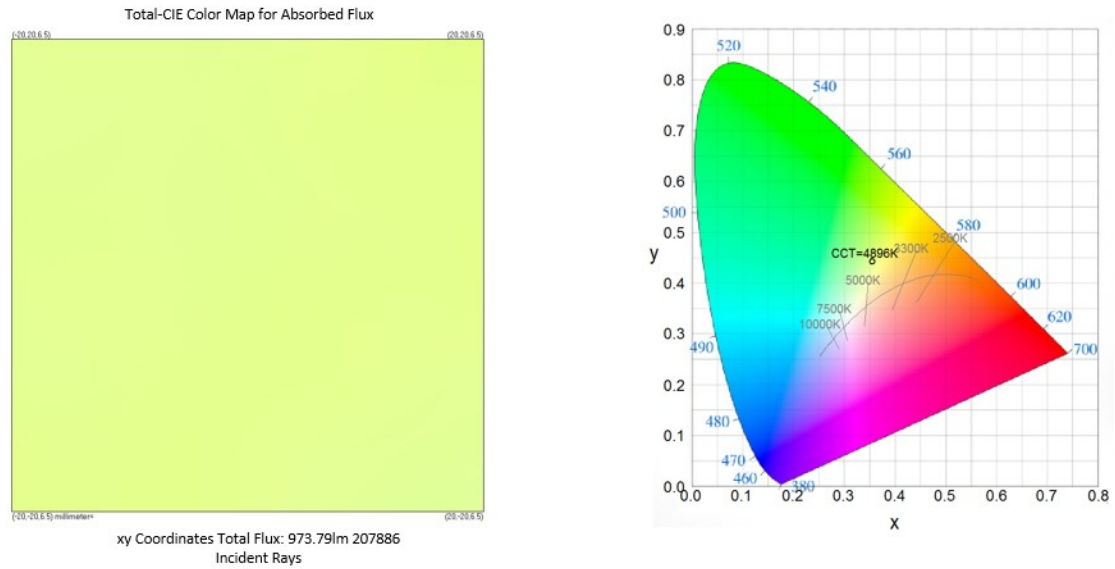


Fig 4. 9: The total CIE Color Map of BenQ liquid crystal display backlight LED after simulation

With the decrease of CCT, the white color light tends to be warmer. The performance of the color changes gradually from the pure white pink to pale orange and finally changes to deep orange. The left Figure in Figures 4.8 and 4.9 shows the backlight is the specific color. The color of AOC appears pink which is normal. However, the color of AOC turns to be green as the normal CCT of about 4900K. We can see from the spectral characteristics of ordinary white LED in Fig 4.7 (a) that in addition to the blue light, green light also takes a high proportion in the energy of light while the red color was the lowest one. Obviously, after cutting down the blue light directly, green light becomes the highest light of most energy and it lead to the result of the simulation.

4.3 New filtering method of blue light through hardware

4.3.1 New proposal of combining two kinds of LED in backlighting to filter blue light

The above two companies have successfully applied the hardware methods of filtering blue light to product, and they have done a great breakthrough compared to the traditional software methods. However, there will still be a certain degree of color cast and the CCT will also be significantly reduced.

Therefore, we propose a new filtering method of blue light through hardware to maintain the basic CCT and prevent the color cast phenomenon of LCD device at the

same time. Currently, there are two types of white LED: one is the single-core light-emitting device which uses blue LED as a substrate and then stimulate the red and green light by the blue phosphor to get white light. Another is the three-core light-emitting device that uses three independent RGB LED chip and get the white light through the mixture of them. At present, the former white LED is widely used because it is more energy efficient and much cheaper than the latter. Additionally, the former one can be made in ultra-thin size which is suitable for LCD backlighting.

However, the emission of white light by single-core has some natural features because of its light-emitting principle. Our study is aimed to give a new proposal associated with these features. In the traditional blue-light-excited white LED spectral distribution, the energy concentrates in the area of the blue light, the wavelength band around 440-450nm. This band is considered to be the most harmful band according to other research. Due to the excitation characteristics of the phosphor, there is a depression at about 490-520nm in the band of cyan light. Therefore, we have proposed a new method that reduces the blue light at the wavelength of 440-450nm, while adding the specific 490nm cyan light led to compensate for this spectral depression. It is possible to adjust the spectrum distribution so as to achieve compensation for CCT.

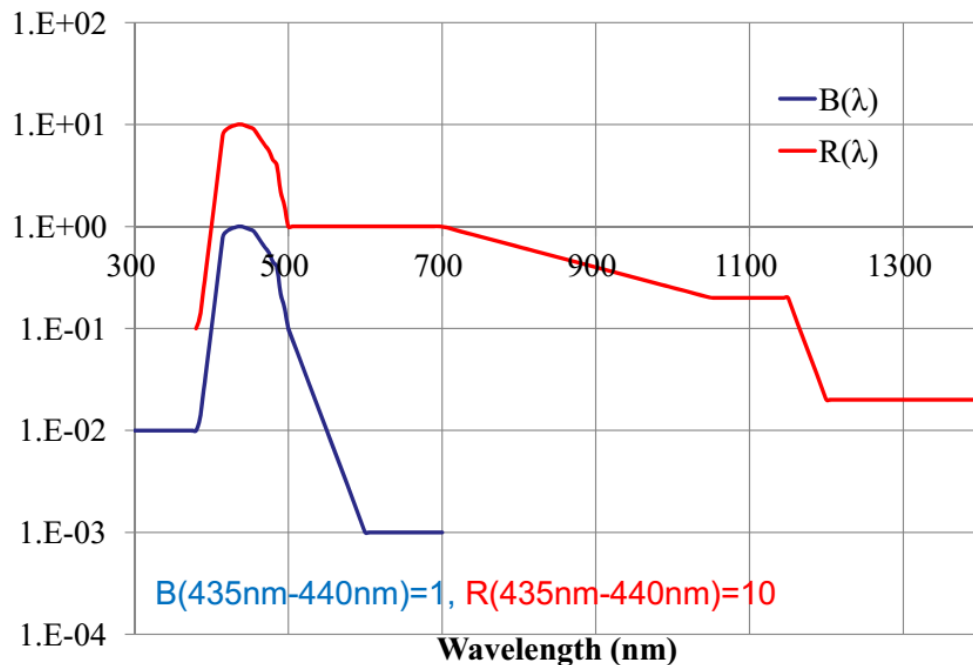


Fig 4. 10: Spectral weighting functions for the $B(\lambda)$ and $R(\lambda)$ retinal hazard from IEC 62471

Fig 4.10 shows the function curves for the "retinal thermal" ($R(\lambda)$) and "retinal photochemical" ($B(\lambda)$) hazard types of relevance for LEDs. According to the current IEC standard of blue light hazards, the band around 490nm has been far away from this dangerous area. In accordance with IEC 62471 published data, the hazard value of the band of 435nm and 440nm is 1, while the value of 490nm band has been reduced to 0.22.

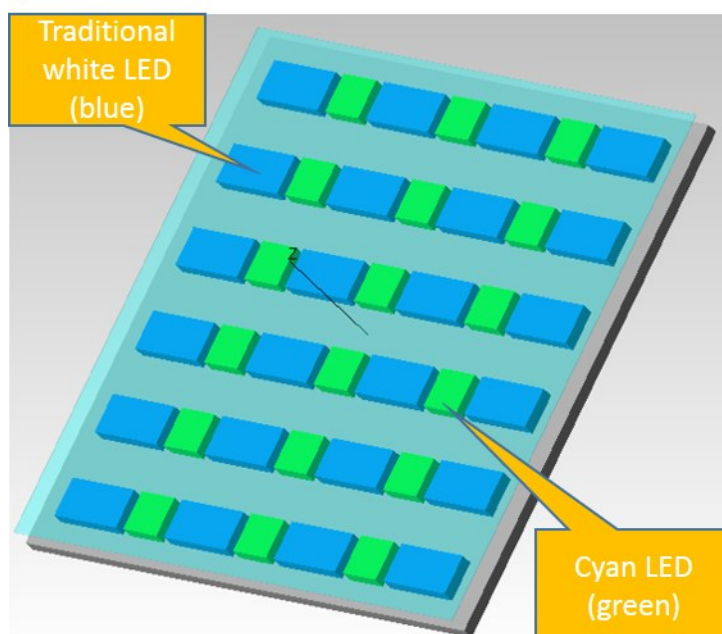


Fig 4. 11: Backlight panel model of our method of filtering blue light

Fig 4. 11 shows the proposal backlight panel model with our method of filtering blue light towards problems in other methods through hardware. We have added a new cyan LED at wavelength of around 490nm in the traditional white LED between intervals. Cyan LED is shown at green color in Fig 4.11. The energy of these LEDs do not need to be too high because the function of them is the color complement after applying blue light filtering technology, making the color shift and CCT reduction minimized.

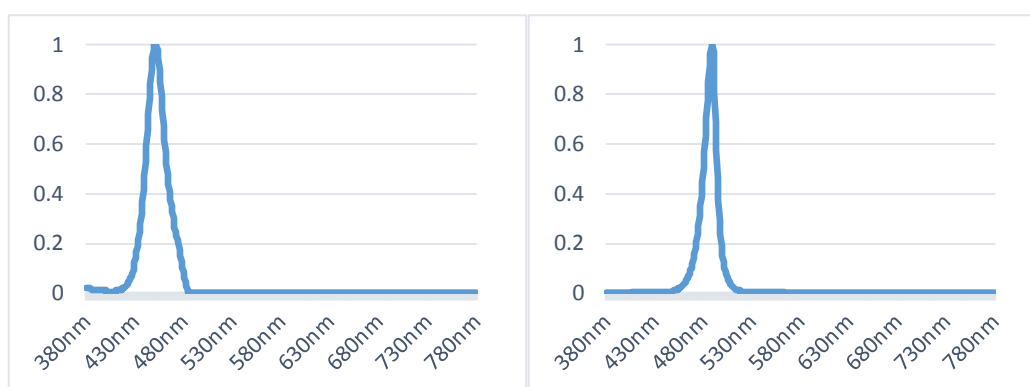
4.3.2 Analysis and calculation of CRI and CCT

CCT and CRI are the most important indicators of the spectral color. CCT is the most common indicator of the spectral quality of a light source, while the CRI is used to measure the degree of color reduction. D65 light source as a standard light source is often of a CCT of 6500K, the CCT reference is noon CCT of sunlight. The CRI of the

solar spectrum is defined as a maximum of 100. The closer to 100 the CRI, the better light source restores the color. Incidentally, the CRI of the incandescent lamp is also defined as 100 but the CCT of the incandescent lamp is about 3000K. However, as the backlight of the display, such CCT is not suitable. Therefore, we have mainly calculated about comparing the solar spectrum CCT and CRI for simulation and analysis.

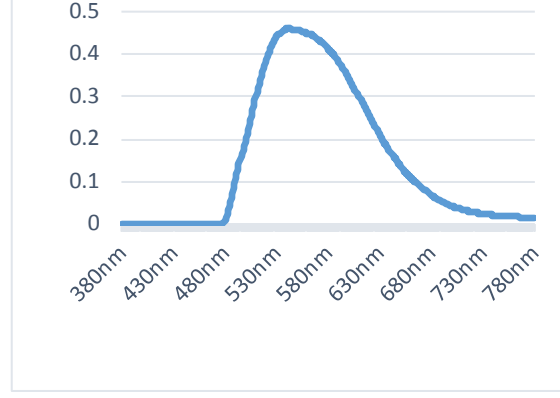
The spectral curve in (a) of Fig 4.12 is the spectrum of the harmful blue light spectrum to be filtered out in this article, while in (b), the cyan light added to balance the spectrum. (c) is the spectrum of the red and green bands remaining after the original white LED was filtered. Since the decrease proportion of blue light energy and the increase proportion of cyan energy needs to be analyzed. We split the original spectrum into three separate spectrums for analysis and discussion of final synthetic spectrum.

In this background, we use the spectral fitting method to deal with this problem, through the target spectrum (solar spectrum) to carry out resolution and principal component analysis LED spectral distribution, and by least squares fitting simulation target spectrum, and then get the corresponding energy comparison coefficient. Although the main method of spectral fitting is iterative algorithm, including the fastest gradient method published by NIST [19], however, least squares method has the advantages of high efficiency and convenient operation to the matrix. We have applied the least square method to calculate.



(a) Partially filtered blue light spectrum

(b) Added cyan spectrum



(c) Red-green spectrum in the original white

Fig 4. 12: Three independent spectrum after splitting in the study

First, according to the principle of spectral superposition LED spectral synthesis model [20]

$$L(\lambda) = \sum k_i S_i(\lambda) \quad (1)$$

Spectral discrete sampling, construct the target spectral matrix,

$$S(t) = [y_1, y_2, y_3, \dots, y_t]^T \quad (2)$$

t is the number of discrete sampling points of the target spectrum.

Construct the LED spectral matrix $S_{LED}(i)$ and LED unit $N_i(t)$,

$$S_{LED}(i) = [N_1(t), N_2(t), \dots, N_i(t)]^T \quad (3)$$

t is the number of discrete sampling points of the LED unit and i is the number of fitting units to determine the size of the fitting matrix and simulation accuracy. The more LEDs there are, the more accurate the simulation is.

Construct the coefficient matrix $K = [k_1, k_2, \dots, k_i]^T$ and obtain the fitting formula

$$S_{LED}(i)K = S(t) \quad (4)$$

The coefficients are calculated by the formula (4). Because $i \ll t$, the calculation is the solving process of the overdetermined equation while the overdetermined system has no classical solution but its generalized solution can be obtained, that is least squares solution K^*

$$\|S(t) - S_{LED}(i)K^*\|_2 = \min_{K \in R^i} \|S(t) - S_{LED}K\|_2 \quad (5)$$

Here we will take the three-independent spectral matrix into the LED spectral synthesis model

$$S_{LED}(i) = [S_{blue}, S_{cyan}, S_{GR}] \quad (6)$$

The solar spectrum is then used as the fitting target spectrum and let it be

$$S(t) = S_{solar}(t) \quad (7)$$

By solving the overdetermined equation of this structure, we obtain three coefficient solutions.

$$\begin{bmatrix} k_{blue} \\ k_{cyan} \\ k_{GR} \end{bmatrix} = \begin{bmatrix} 1.3832 \\ 1.1046 \\ 2.4783 \end{bmatrix} \quad (8)$$

From the results of the coefficients in (8), we have clarified that the energy of the blue part is about half of the energy of the red-green part. We assume that the energy of the red-green light is the same as that of the original white LED, it means that the blue part of the energy is filtered out by about 50%. In the meantime, the proportion of cyan light increase is less than 50%, it is considered part of the increased cyan did not bring new blue light hazards.

Since the fitting target of this simulation is the solar spectrum, we can see from this ratio of the coefficients K that the damage of the blue light in the real solar spectrum is very little, approximately equal to about half of the white LED in the case of the same transmit power, as shown in Fig 4.13.

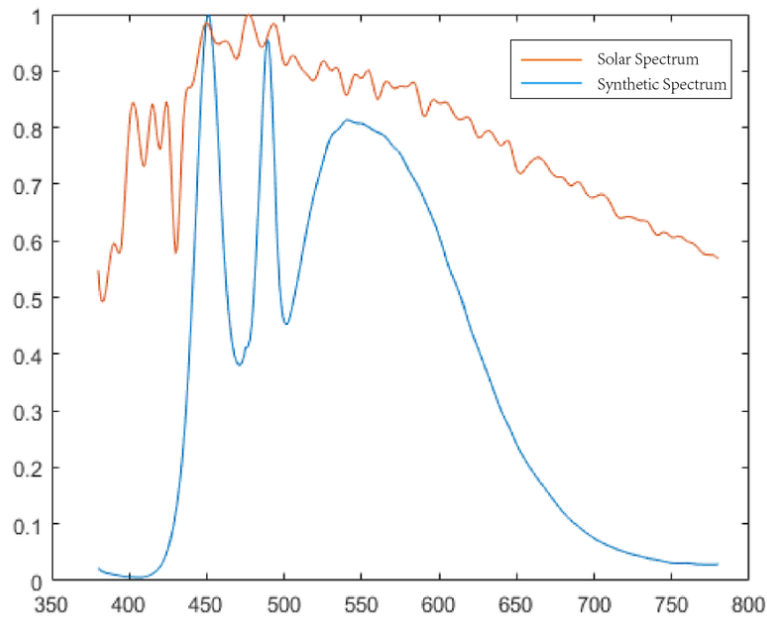


Fig 4. 13: Comparison of the synthetic and solar spectral of the filtered blue light

Then, we have calculated the correlated CCT and color-rendering index by programming, and the spectral curve of the fitting result, as shown in Fig 4.14. From

the calculated results in Fig 4.14, we have obtained the CCT value is 5774.8K after fitting, the CRI is 73.8647 and this result is close to the AOC hardware method. We hope that the CCT can reach more than 6000K. At the same time, the CRI can be further improved. Taking into account the fitting of the solar spectrum is only a way to improve the CRI of a means but did not increase the CCT. Therefore, under the premise that 50% is filtered, we need to modify the green light energy proportion. Here, the energy proportion coefficient of cyan light was adjusted to 1.5 times and 2 times and then a new spectral synthetic curve was obtained and the corresponding results were calculated.

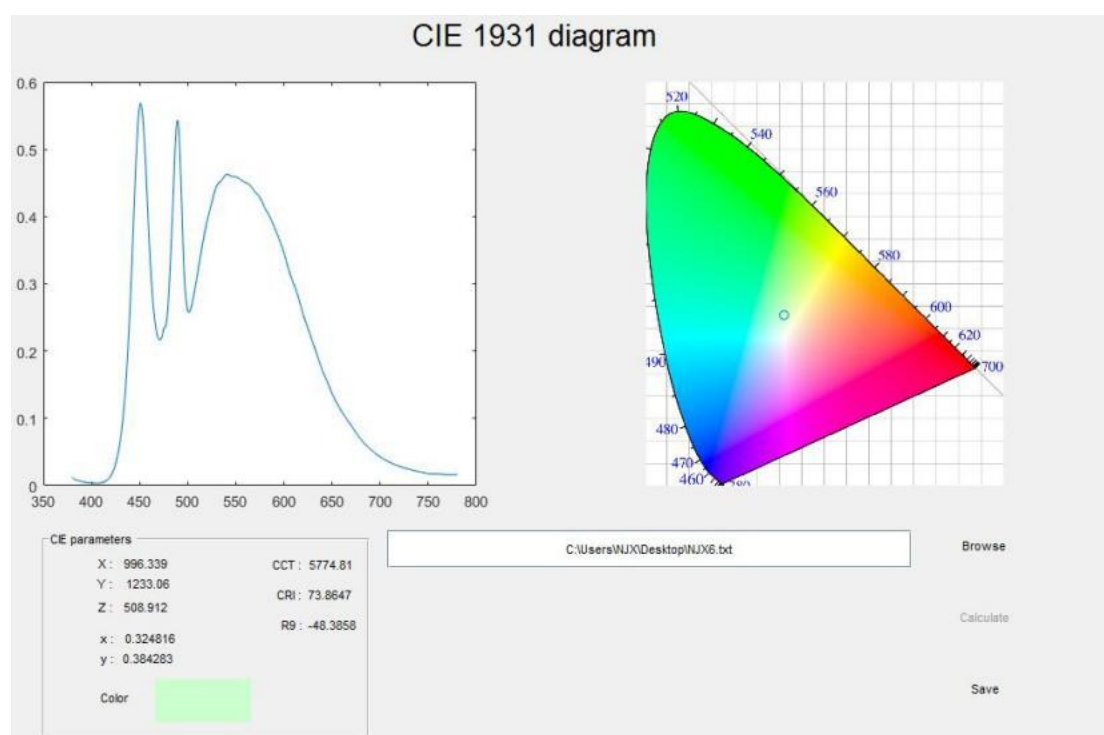
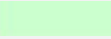
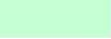


Fig 4. 14: Correlation between CCT and CRI after spectral fitting and color gamut calibration

From Table 2, when the proportion of cyan light energy increase to 1.5 times, the CCT continue to increase but the CRI decreased instead. We consider that 1.5 times the proportion of the original spectral fitting of the cyan coefficient is the most appropriate.

Table 4. 2: The effect of the proportion of cyan energy on the CCT and CRI of the synthetic spectrum

Percentage of cyan light energy	CIExy	CCT(K)	CRI	Color appearance
1	(0.32, 0.38)	5774.81	73.86	
1.5	(0.32, 0.38)	6081.23	74.82	
2	(0.30, 0.36)	7061.52	73.17	

4.4 Result

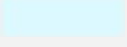
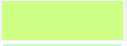
After applying the hardware methods, the three designs of blue backlight panel have several key optical parameters that need to be discussed. The first is the color performance such as CCT, followed by the LMS color analysis for the human eye. Moreover, the related calculation and analysis for blue light hazards to the human eye retinal.

4.4.1 A comparison of optical parameters between our proposal and two existence ones

Using the program which shown in Fig 4.14, we have calculated the optical parameters and have obtained the color performance of other two hardware blue light filtering methods.

Table 4.3 shows calculation results of the light-color performance for four LED backlight systems. From these results, the LED of AOC has the best performance in CRI. However, compared to the standard 6500K sunlight CCT, there is a sharp decrease. 6500K is the most suitable and standard CCT for the vision of humankind. On the other hand, the mechanism of filtering blue light of BenQ indicate that it will take worst performance both on CCT and CRI, and it is also testified in Table 4.3. Our proposed method is the closest to standard CCT and also has a good performance in CRI which almost as same as ordinary white LED.

Table 4. 3: Ordinary white LED and three kinds of hardware filter blue optical parameters comparison

Different types of LED backlight	CIExy	CCT(K)	CRI	Color appearance
Ordinary white LED	(0.305836, 0.326304)	6914.24	74.5182	
AOC	(0.325552, 0.338874)	5813.66	77.4582	
BenQ	(0.370761, 0.462893)	4658.89	63.6568	
Our proposal	(0.316706, 0.378753)	6081.23	74.817	

4.4.2 The calculation of LMS cone cell response on human eyes

Above we have conducted the simulation on the objective evaluation of the display parameters. Then, we conduct some calculation associated with the subjective evaluation of the human visual system. The visual process of the human eye is through the visible light perceive things. Visible light with spectral distribution goes through the cornea, pupil, and the lens and reaches the retina of the human eye back. Then, it is absorbed by the three types of cone cells on the retina, forming a visual response to the color of the three-dimensional. The human eye has three types of cone cells. Each cone cells absorbs light and fuses the spectra of all the wavelengths incident on it into three signals L, M and S. As shown in equation (9). This process also becomes the design principle for all color measurement and radiation detectors [21].

$$\left. \begin{aligned} L &= \int L(\lambda)E(\lambda)d\lambda \\ M &= \int M(\lambda)E(\lambda)d\lambda \\ S &= \int S(\lambda)E(\lambda)d\lambda \end{aligned} \right\} \quad (9)$$

$E(\lambda)$ is the incident $L(\lambda)$, $M(\lambda)$, $S(\lambda)$ spectrum, are respectively spectral response of L, M and S cone cell.

The spectral response functions corresponding to L, M, S cone cells are shown in Fig 4.15,

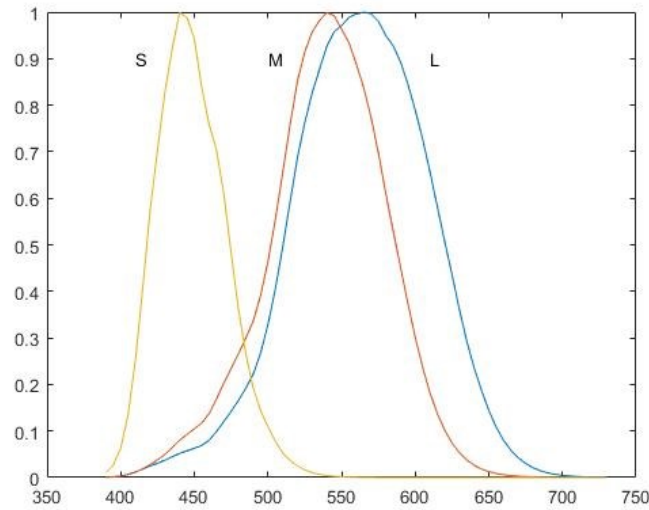


Fig 4. 15: Spectral response functions corresponding to L, M, S cone cells

Fig 4.15 clearly show that both the L and M bands have a broad spectrum of cone responses. Although the response peak wavelengths are slightly different, the response spectrum covers three RGB Color band while the S-band pyramidal cell response is relatively too narrow to cover more bands. Table 4 clearly show the effect of three kinds of blue filters backlight panel on the response values of LMS human cone cells. Compared with the ordinary white LEDs without blue light filters, the response values of the L and M bands in our proposal is almost the same which also means the response of red and green is the same as ordinary white LEDs. On the other hand, due to the proposal of filtering of harmful blue band at 450nm which mentioned in relative works[18][22] along with the addition of cyan band at 490nm which mentioned in introduction[14], there have been a certain average in the effect. The response of S-band is reduced to some extent based on the adjustment of spectrum on blue light.

Table 4. 4: L, M, and S cone cell signal response for different types of LED backlight

Different types of LED backlight	L	M	S
Ordinary white LED	8.60	7.35	4.57
AOC	8.73	7.20	3.81
BenQ	8.44	7.04	1.26
Our proposal	8.96	7.83	3.28

As for the AOC's method, because of its spectrum has only a 10nm shift from the original white LED spectrum, the original white LED spectral change is minimal and therefore the responses of its L and M cone wave cells in the two bands is very close to the response of the ordinary white LED in the same position. However, because of its

blue light band shift is the overall movement of the high energy peak wavelength, the S-band cone cell response will be reduced compared to the original white LED at the same position.

Finally, BenQ's method is to directly filter out the entire band of blue light below 455nm while the other band did not change. According to Fig 4.15, L and M-band cone response curve, we have shown that the response below 455 nm has been significantly reduced. Therefore, the BenQ calculation results of the L and M response values are slightly decreased only compared to the ordinary white LED at the same position. BenQ only filter out the entire band of blue light below 455nm, resulting in the sharp drop of S-band response results from 4.5740 to 1.2591 compared to ordinary white LED. It naturally cause serious color cast effect which means we can hardly distinguish colors from the display system.

4.4.3 The Calculation of Weight of Blue Light Hazard

IEC 62471-2006[29] was the common standard of Photobiological Safety of Lamps and Lamp Systems while currently the most detailed definition of the Blue Light Hazard is ICE 62778- 2014 standard [30]. ICE 62778- 2014 is the supplement of IEC 62471 for the assessment of blue light hazard to light sources and luminaires. It mainly evaluates light biosafety of light sources and light source systems and give the evaluation criteria and calculation methods of response. Our research on reducing blue light hazard is based on ICE 62778-2014.

Some research also has done a lot of experiments to evaluate the risk assessment form exposure to LED [31].The purpose of their research is focus on the evaluation of blue light hazard, therefore they do not need to compare types of blue light filtering panel. Therefore, even under the same standard of ICE 62471, differ to our research, the time and power have been concerned in their research which means our research is just a comparison of blue light hazard without concerning of time and the power of light sources.

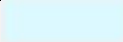
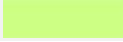
In order to protect the retina from long-term exposure and cause harm, the relationship between spectral radiance of the optical radiation source $L(\lambda)$, the blue light hazard function $B(\lambda)$ and blue light weighted brightness is as follows:

$$L_B = \sum_{\lambda=300}^{700} L_{\lambda}(\lambda, t) \cdot B(\lambda) \cdot \Delta\lambda \leq 100W \cdot m^{-2} \cdot sr^{-1} \quad (t > 10^4 s) \quad (10)$$

L_B is Retinal light damage, $L_{\lambda}(\lambda, t)$ is the spectral radiance, the unit is $W \cdot m^{-2} \cdot sr^{-1}$. $B(\lambda)$ is the blue light hazard weighted index. $\Delta\lambda$ is Bandwidth (nm). t is exposure time (s).

Base on the formula of blue light hazard, we calculate the different types of LED backlight blue light damage.

Table 4. 5: Different types of LED backlight blue light damage

Different types of LED backlight	CIExy	CCT(K)	CRI	Color appearance	L_B
Ordinary white LED	(0.31, 0.33)	6914.24	74.51		4.81
AOC	(0.33, 0.34)	5813.66	77.46		4.04
BenQ	(0.37, 0.46)	4658.89	63.66		1.40
Our proposal	(0.32, 0.38)	6081.23	74.81		3.59

From Table 4.5, we can see that before the blue light is not filtered out, ordinary white LED light spectrum is of the greatest value of the blue light hazard. Based on the result above, BenQ's blue light filter solution minimized the harm value of the blue light hazard best while getting the worst color performance. On the other hand, the method of AOC performed best at color performance but it got a bad result in reducing the blue light hazard. Our proposal, however, obtained a balance between reducing the blue light hazard and maintaining high color performance which be showed in Table 4.3.

4.5 Result

Recently, many manufacturers have begun to focus on the blue light filtering to reduce the harm of blue light on human. Software modeling and numerical analysis to prove that hardware methods is better than software methods is used. In this paper, we have proposed a new type of hardware method of filtering blue light, and have compared between BenQ and AOC's methods. From these analysis, we have shown the advantages and disadvantages of these three kinds of hardware methods.

To achieve the complete safety of blue light filtering out or minimizing the blue light hazard, it must be at the expense of the high-quality of the color. According to all the simulation results and parameters of the comparison, we consider that our proposal enable to balance the reduction of blue light hazard and maintaining good color performance.

As future work, we can see that multi-spectral inversion algorithm is still incomplete. In this paper, we have tried to adjust the coefficients to get the best effect, and this adjustment is still very rough. In addition, we may consider the setting a number of narrowband LED near the cyan light instead of a single cyan light LED or using a wider spectrum of cyan light LED. We may obtain better results in the resulting fitting spectrum by the use of this broadband cyan light LED combined with a multispectral inversion algorithm.

Chapter 5 Headlight lamp of automobile

5.1 Background

High-beam headlamps play a crucial role in nighttime driving. Using numerical analysis, this study investigates two essential optical characteristics of these. We have proposed a simple car model with standard high-beam lamps that use new types of high-power light-emitting diodes (LED). Two experiments were performed using this model. First, we assessed the energy loss by using visual simulation. Then, a reflective sheet is added to enhance the reflectivity of the lamp base in order to improve the energy efficiency, and it is proved useful at short distances. Second, we established a spectral attenuation model of mist in the visible spectrum. In this model, we evaluated the effect of a high-beam lamp with two different color temperatures on light transmission in mist. There is only a small difference between the two simulation results. Based on the spectral attenuation model of mist, we assumed a similar spectral attenuation model of fog, and then evaluated the effect of a high-beam lamp with different color temperature on light transmission in fog. The calculation result proved that a low color-temperature high-beam lamp achieves greater light transmission than a low color-temperature lamp in fog. Based on the simulation result for the various color temperature effects in various weather conditions, a double color-temperature high-beam lamp has been proposed and the simulation results verify its effectiveness.

A high-beam headlamp is a product that consumers commonly customize according to their needs. Low-beam and high-beam lamps are essential for nighttime driving. However, consumers tend to replace the high-beam lamps in their private cars more frequently than they do the low-beam lamps. The reason is that sometimes a high beam is much more important than a low beam especially on an expressway or on misty day when the optical characteristics of the environment change significantly.

In this study, we focus on two significant parameters for evaluating which high-beam lamp is the best choice. These two parameters are luminous flux and the correlated color temperature (CCT). Luminous flux is the parameter used to estimate the radiation power that the human eye can perceive. Some manufacturers such as General Electric Company (GE), PHILIPS, and OSRAM prefer to directly use the radiation power of a lamp rather than luminous flux to evaluate the output of a high-beam lamp. However, because of differences in efficiency (lumens/watt), the lumen output of different types

of lamps varies even at the same radiation power. This study focusses on the output of a high-beam lamp using luminous flux as the subject of a numerical analysis of the visual effects. The CCT is another essential parameter, which is used to measure the quality of white light. A beam with a high CCT enhances the alertness of drivers, thus reducing the rate of occurrence of traffic accidents. For this reason, a high-CCT beam is widely used in nighttime driving. In contrast, a beam with low CCT does the opposite. However, the transmission of a high-CCT beam is lower than that of a low-CCT beam, especially on a misty and rainy day. In this study, we simulate using both high- and low-CCT beams to evaluate the transmission of a high beam for the ideal spectral attenuation model of light at a particular mist level.

5.2 Analysis and improvements of losses of emitted light energy

5.2.1 Analysis and improvement of losses of the emitted light energy from one lamp

Because any type of high-beam lamp needs a high power supply from a circuit board, the size of the base occupies a fixed space at the bottom of the reflection bowl (the blue portion of Fig 5.1). Considering that the light source is close to the base, the loss of energy is huge.

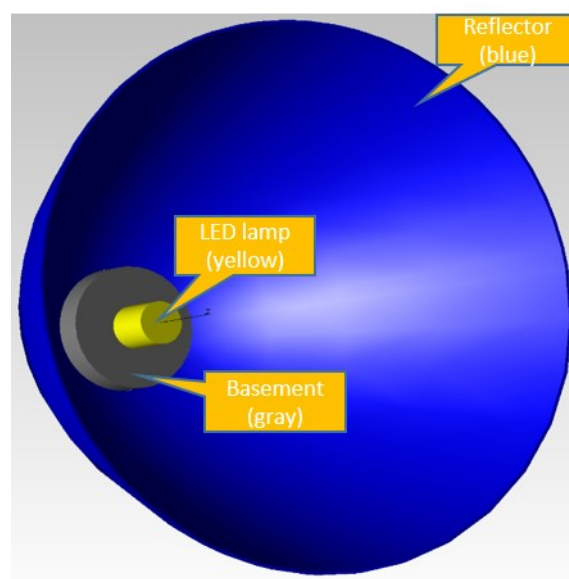


Fig 5. 1: Simplified model of an integrated high-beam lamp

The model of a high-beam lamp shown in Fig 5.1 has been set up based on an actual H7 high-beam lamp. Utilizing Monte-Carlo ray tracing and a broad class of computational algorithms, we applied a number of similar parameters to our model, and we obtained the simulation result shown in Fig 5.2.

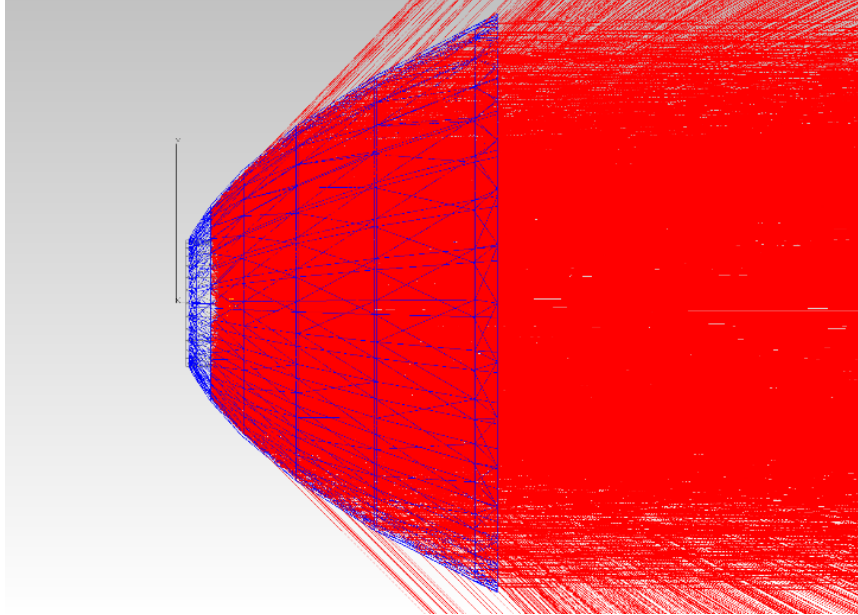


Fig 5. 2: Simplified model of the integrated high-beam lamp with a low-reflectivity base

Because the reflectivity of the base is assumed to be relatively low [6], we can approximate it as an absorber. The lamp used in this model is a high-power LED light source utilized in many fields [38]. The rated luminous flux is 4,022 lm. The simulation result shows that the luminous flux from the front of the high-beam lamp is 2,686.3 lm, which means an energy loss of 36%. Considering that one car is fitted with two high-beam lamps, the amount of energy loss is significant. To solve this problem, we propose adding a reflective sheet between the LED lamp head and the base as shown in Fig 5.3.

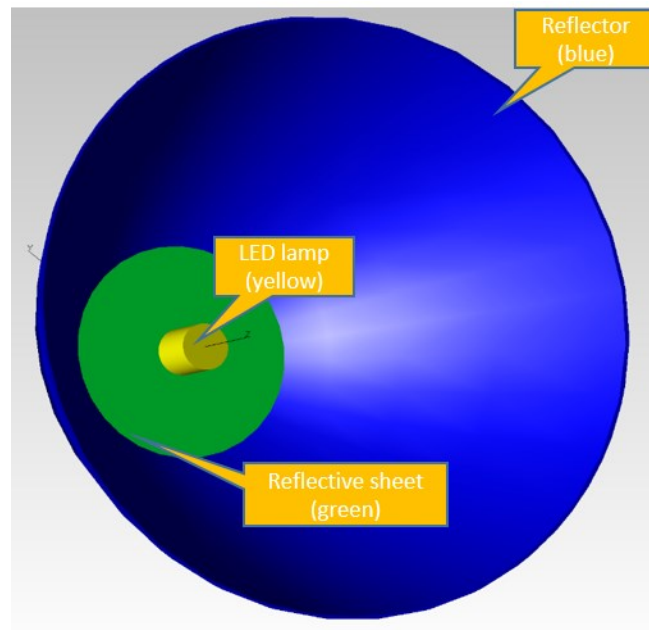


Fig 5. 3: Reflective sheet installed behind the lamp head of the high-beam lamp

The flat green color seen is the reflective sheet that is used to prevent the backward radiating light from being absorbed by the base. A test panel is used to receive the emitted rays. Each ray carries energy from the light source. By collating the received rays from the receiving panel, the luminous flux can be obtained.

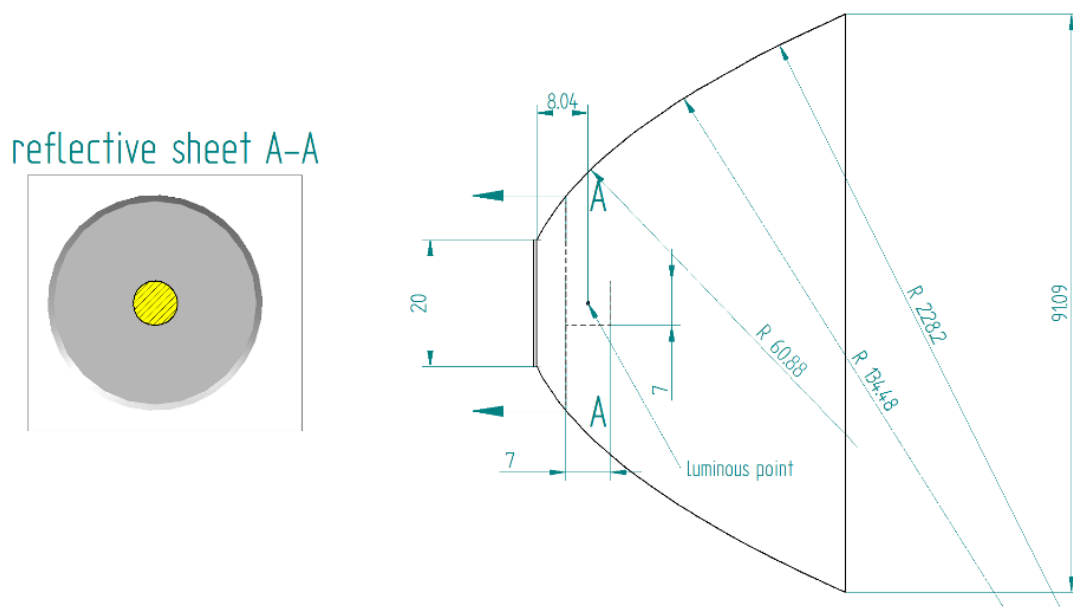


Fig 5. 4: Diagram of the high-beam lamp

Fig 5.4 shows the position of reflective sheet and light source beside a diagram of the dimensions of the lamp. The reflector here has a conical shape. Although other

reflectors have various forms, for the purposes of this experiment, it will not affect the results. The material of the reflective sheet is that of a perfect mirror in order to simplify the analysis. This eliminates the variation due to the variety of reflective materials used by lamp manufacturers. In addition, the reflection properties such as diffuse reflection vary from material to material.

The reflective sheet is located at the junction of the tube of lamp and the base. The shape of the reflective sheet is a flat surface. A curved surface was not used because a curved surface would have a significant effect on the distribution of the optical field from the lamp.

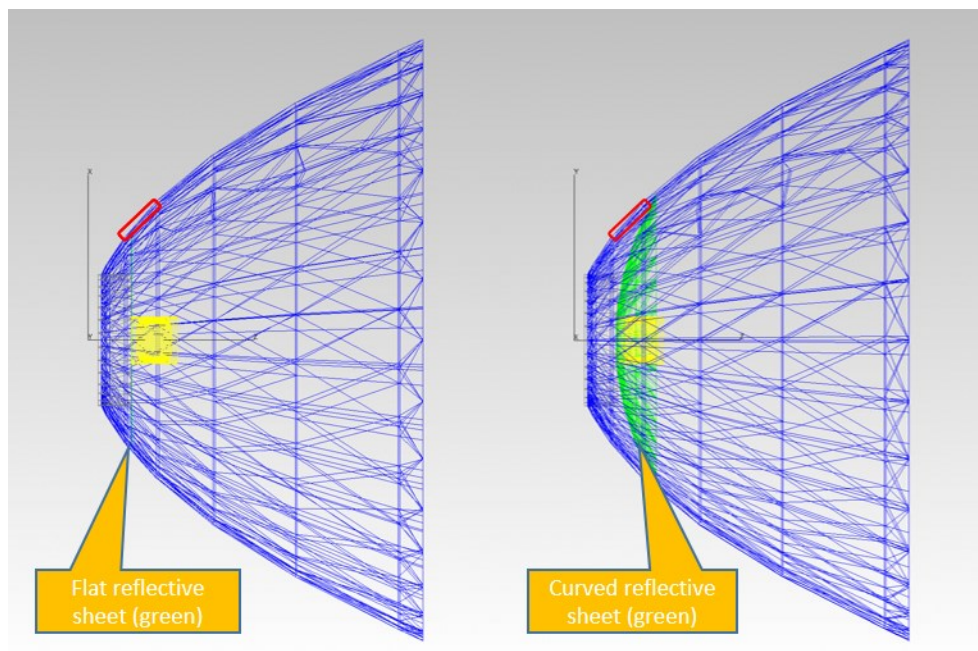


Fig 5. 5: High-beam lamp with reflective sheets with flat and curved surfaces

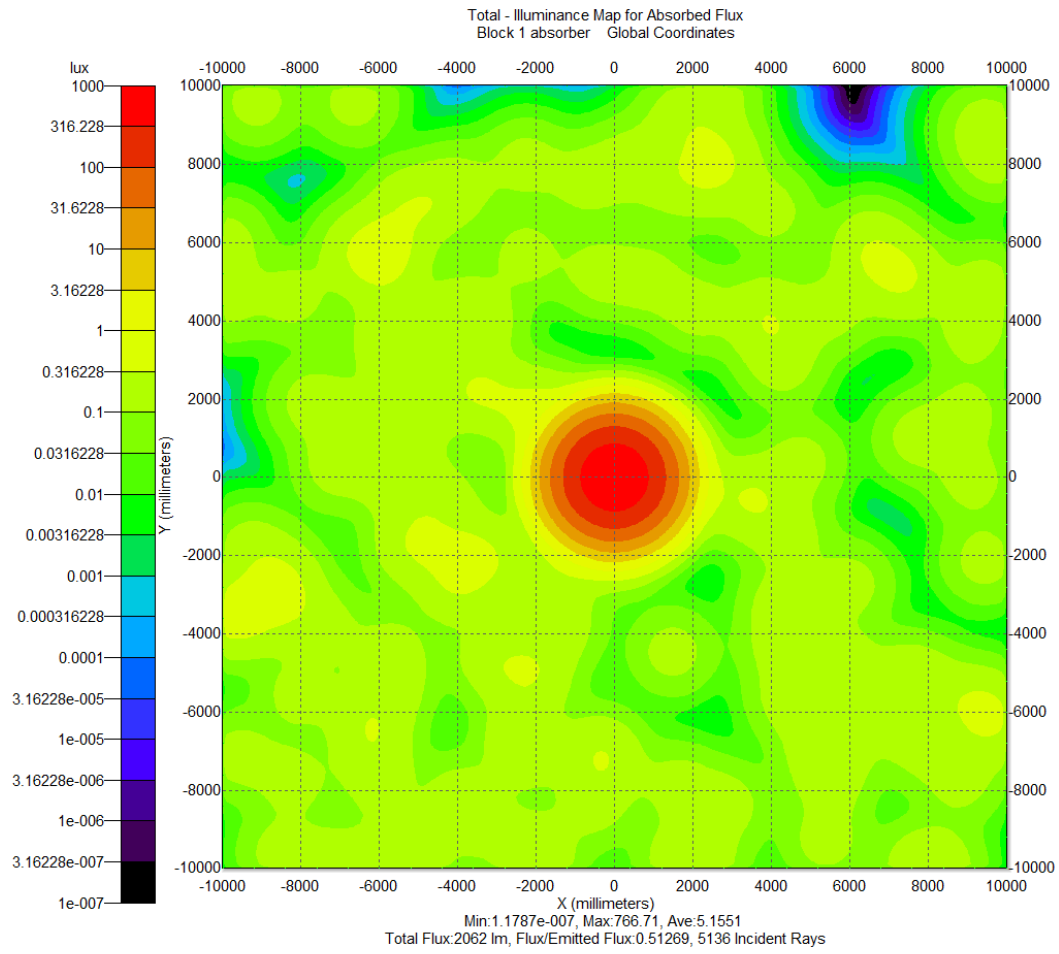


Fig 5. 6: Illuminance map of the absorbed flux of a high-beam lamp without a reflective sheet at 50 m

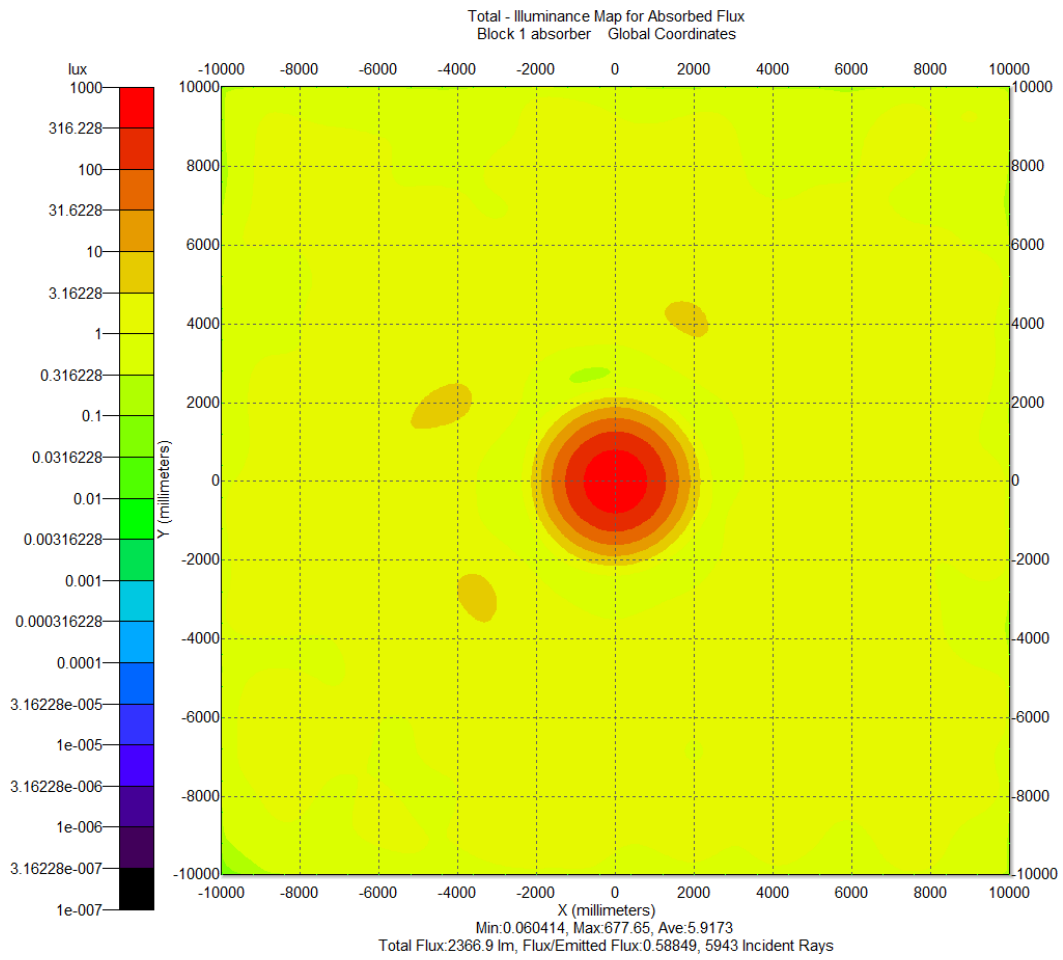


Fig 5. 7: Illuminance map of the absorbed flux of a high-beam lamp with a flat reflective sheet at 50 m

same in both Figures 5.6 and Fig 5.8; however, the green ring around the high-energy facula in Fig 5.8 shows the differences between the reflective surfaces. From the color bar, we can see that the value of illuminance of this green ring is lower in both the center and the outside compared to the same areas in Fig 5.6 and Fig 5.7. The reason can be illustrated using the red rectangle located in the right-hand side of Fig 5.5. The curved reflective sheet, which covered this area of the reflector, caused the original reflector to become ineffective in this area; furthermore, the curvature radius of the curved reflective sheet is also larger than that of the original reflector in this area. The light emanating from this area was perturbed. In addition, the total flux in Fig 5.8 is not only lower than that of Fig 5.7 but also lower than that of Fig 5.6, which has no reflective sheet. The superior characteristics of the flat reflective sheet have been proved by comparing the results of Fig 5.6 with those in Fig 5.7.

Next, the effectiveness of the flat reflective sheet at various distances is tested.

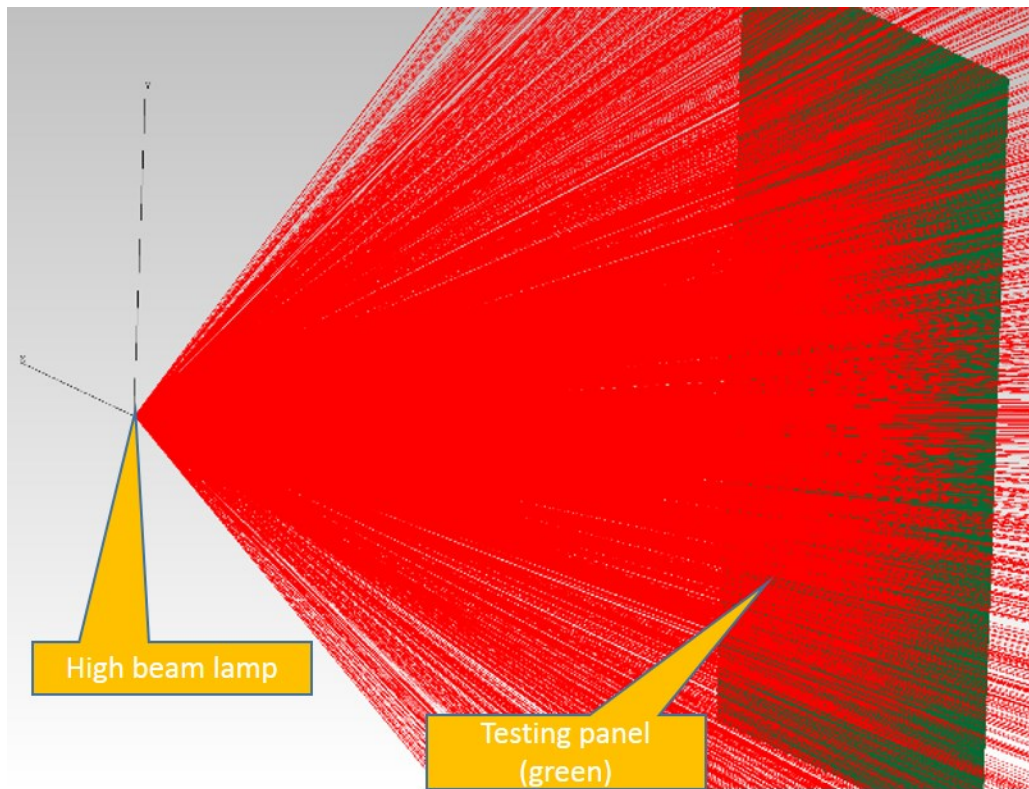


Fig 5. 9: Ray tracing from the high-beam lamp to the test panel

Fig 5.9 shows the rays from the high-beam lamp to the test panel, which is located at a distance of one meter from the lamp. The size of this panel is $20\text{ m} \times 20\text{ m}$. In order to improve the accuracy of the test, a million tracing rays have been used. Compared to the 90 mm-diameter high-beam lamp, the test panel is very large. By changing the distance between the high-beam lamp and the test panel [39], we obtained the outputs

of luminous flux with and without the reflective sheet as showed in Table 5.1.

Table 5. 1: Received luminous flux at different distance with and without a reflective sheet

Distance Luminous Flux	0.1 m	1 m	10 m	20 m	30 m	40 m	50m
Without reflective sheet	2686.30 lm	2686.30 lm	2639.40 lm	2266.80 lm	2148.10 lm	2096.4l m	2062.00 lm
With reflective sheet	4022.00 lm	4022.00 lm	3973.90 lm	3309.30 lm	2903.10 lm	2583.10 lm	2366.90 lm

From Table 5.1, it can be seen that the reflective sheet greatly improves the illumination in the range of distance from 0.1 m to 30 m. An especially large improvement is seen between 0.1 m and 20m. However, the difference becomes smaller and smaller above 50 m; for this reason it was considered unnecessary to analyze the effects beyond 50 m.

5.2.2 Analyzing and improving the loss of emitted light energy from a car

To further test the efficacy of this reflective sheet, we next installed the reflective sheet in two lamps that were separated by the actual distance of the headlamps of a car. Fig 5.10 shows the model of the car with improved high-beam lamps that have the reflective sheet. The distance between the car and test panel is 50 m in Fig 5.10. For this situation, we tested the output of luminous flux from the car using ray tracing from the double high-beam lamps of the car to the test panel.

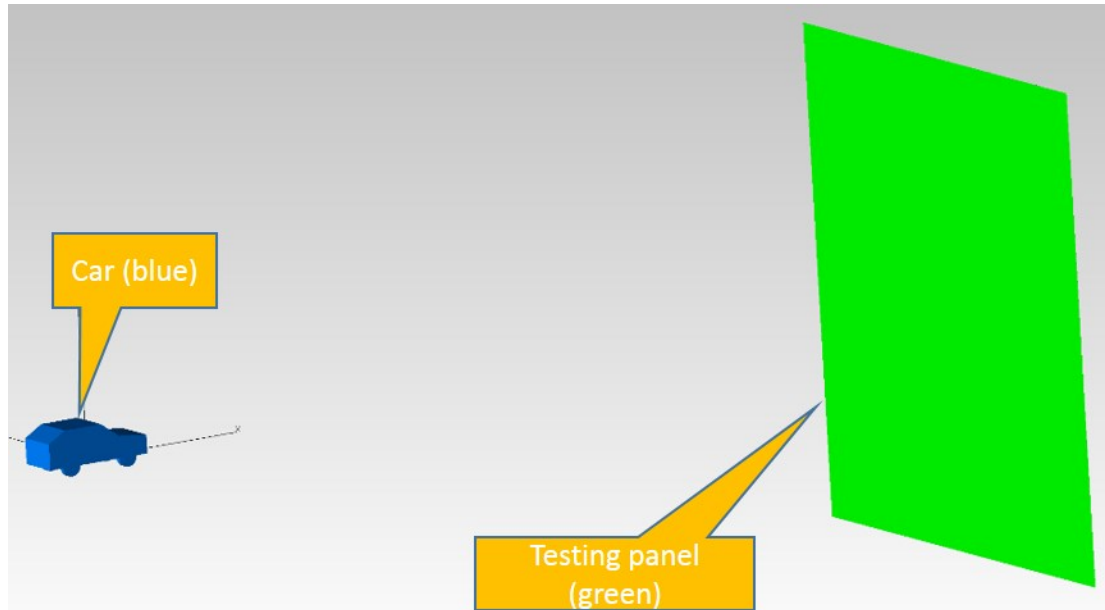


Fig 5. 10: Model of a car with improved high-beam lamps and the test panel

Though ray tracing from the double high-beam lamps of the car, we obtained the ray tracing results shown in Fig 5.11.

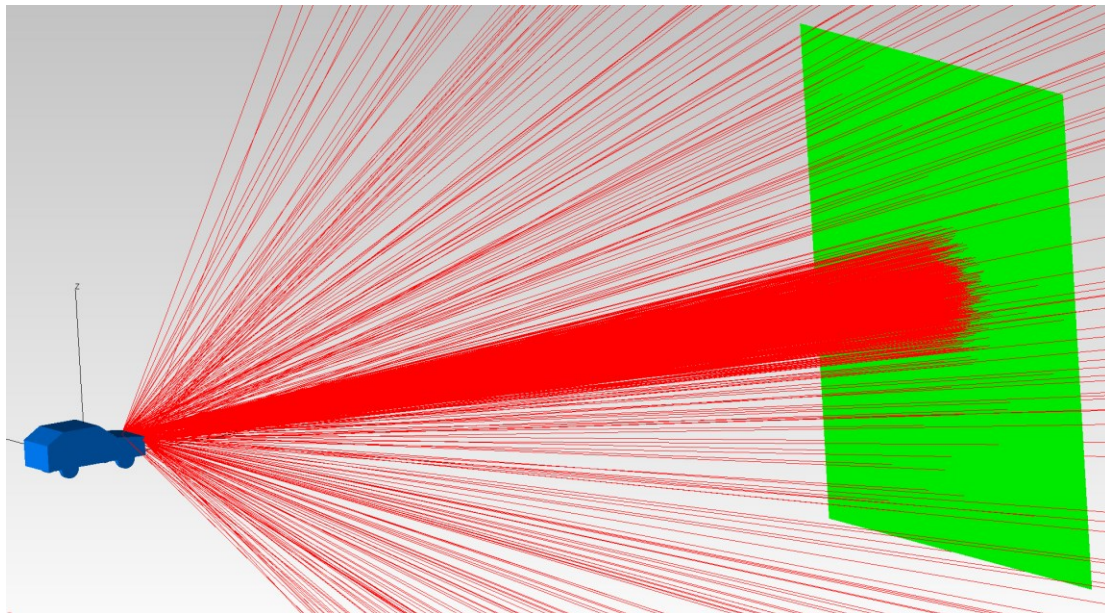


Fig 5. 11: Ray tracing from the double high-beam lamps of a car to the test panel

From Fig 5.11, we can see that, unlike in Fig 5.9, the emitted rays are focused in a sharp cone. Even at less than 50 m distance, the diffusion of rays is not significant. It also means the energy loss of the high-beam lamp is low even for transmission over long distances. The ray tracing performance illustrates how high-beam lamps are intended to function.

Table 5. 2: Received luminous flux at different distances from a car without and with reflective sheets in the headlamps

Distance Luminous Flux	0.1 m	1 m	10 m	20 m	30 m	40 m
Without reflective sheet	6508.00 lm	6508.00 lm	6448.80 lm	5717.50 lm	5486.20 lm	5391.60 lm
With reflective sheet	8000.00 lm	7954.20 lm	7343.90 lm	6210.50 lm	5726.70 lm	5527.10 lm
Distance Luminous Flux	50m	60 m	70 m	80 m	90 m	100 m
Without reflective sheet	5338.30 lm	5303.90 lm	5290.50 lm	5275.80 lm	5271.70 lm	5259.80 lm
With reflective sheet	5416.60 lm	5335.70 lm	5301.00 lm	5275.80 lm	5271.10 lm	5259.80 lm

Because the high beam lamps are used in a car to illuminate a distance range from 0 to 100 m, we added entries for test panel distances from 40 m to 100 m. Table 5.2 shows the luminous flux from a car at various distances that correspond to those in an actual driving situation. The size of the test panel used here is as same as the panel in Fig 5.9, which is 20 m×20 m. The reason for the large size of this panel is that when rays are transmit over a distance of 100 m, even for a small emission angle, the area of the facula is amplified. Fig 5.12 shows the performance of the facula when rays are transmitted over a distance of 100 m.

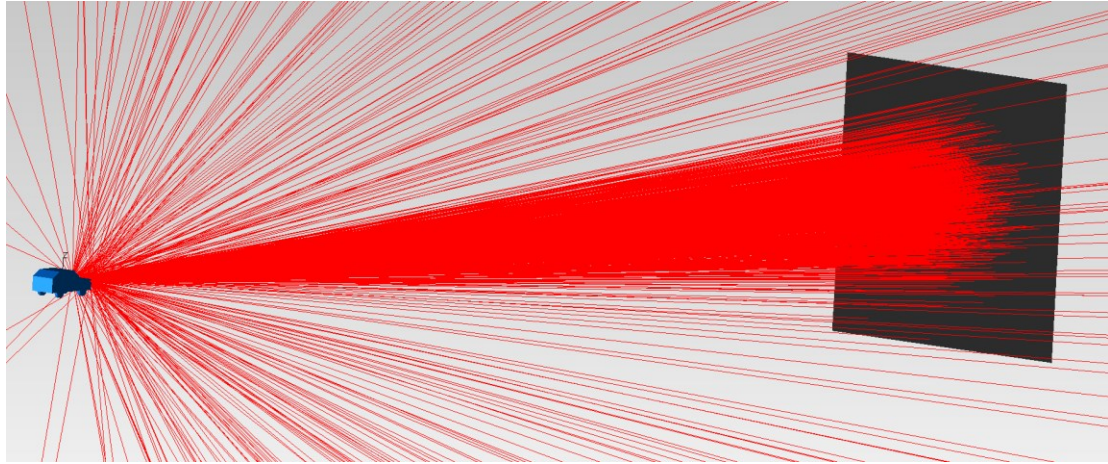


Fig 5. 12: Ray tracing from double high-beam lamps of car to a test panel at a distance of 100 m

The results in Table 5.2 are similar to those in Table 5.1. The most significant difference between Table 1 and Table 2 is the presence of two lamps in Table 5.2. Because the output is doubled, the reflective sheet becomes ineffective at a test panel distance of 50 m.

Luminous flux is only one important parameter in photometry. Another important parameter is illuminance, which is used to evaluate the energy intensity at the illuminated area. This parameter is not only related to the power of the output but also closely related to the vertical area of the illuminated body. Therefore, we adjusted the size of the receiving test panel to test the change of illuminance due to the effects of the reflective sheet in the high-beam lamp.

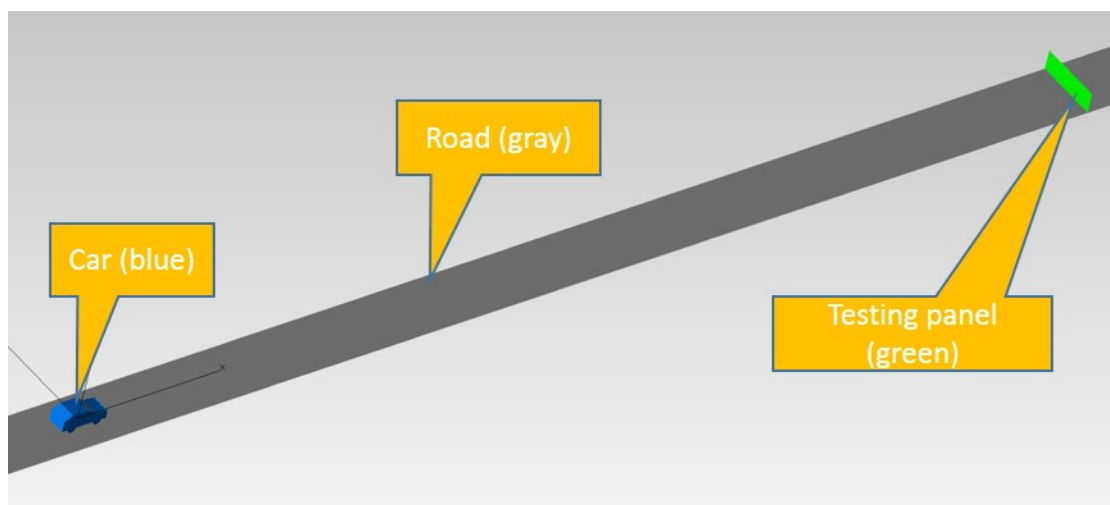


Fig 5. 13: Model of a car with improved high-beam lamps and appropriately sized test panel

To analyze the illuminance of the headlamps of a car, we changed the size of the test panel from 20 m×20 m to 6 m×2 m as depicted in Fig 5.13. We chose the size of the receiving test panel considering vehicle standards from the Japanese Industrial Standards (JIS) [40]. The width of a car is approximately 1.5–2 m, and the height is approximately 1.3–2 m. If the car is being driven on a road, the driver perceives the information from an area of about two car distances to the left and to the right. We therefore set the width of the test panel to 6 m. In addition, we added a model of the road that has the same width as the test panel. In this case, we are evaluating the intensity of luminous flux, so the width does not affect the simulation. We then used this test panel to get the value of illuminance at varying distances.

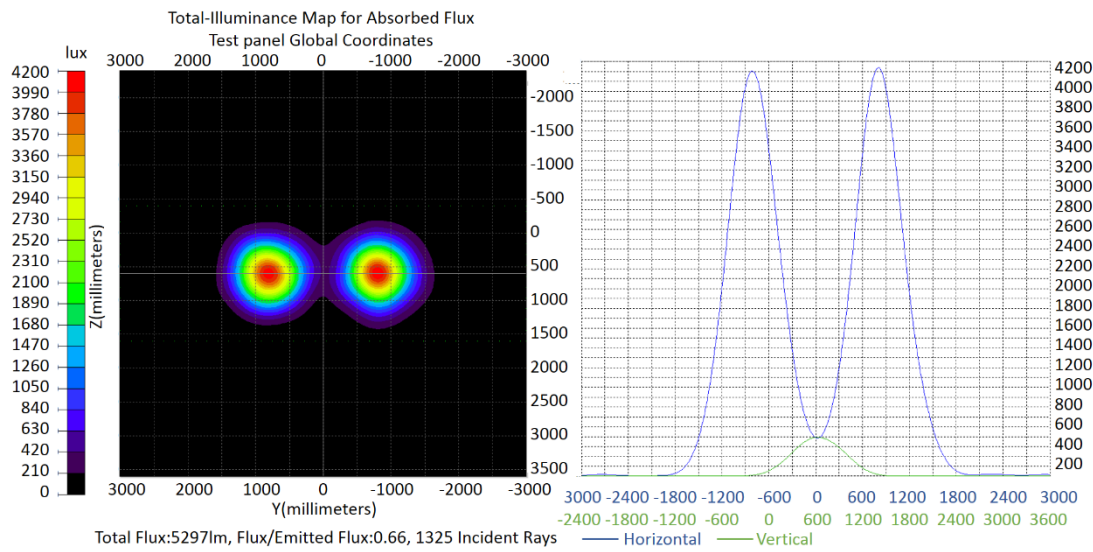


Fig 5. 14: Illuminance map of absorbed flux of car headlamps at a distance of 10 m from the headlamps

Fig 5.14 shows the illuminance map of a test panel that was at a distance of 10m from the car. The left-hand picture shows the distribution of illuminance on the testing panel. The average illuminance can be calculated at this functional interface. The color bar on the left side of Fig 5.14 indicates the value of the illuminance. The red color at the top of the color bar represents the maximum value of illuminance. From the illuminance distribution, we can see that in the center of the lamp, the value of illuminance is a maximum and the value decreases from the center to the edge. The right-hand picture contains profiles indicating the values of illuminance. The blue profile is data from the horizontal direction and the green profile is data from the vertical direction.

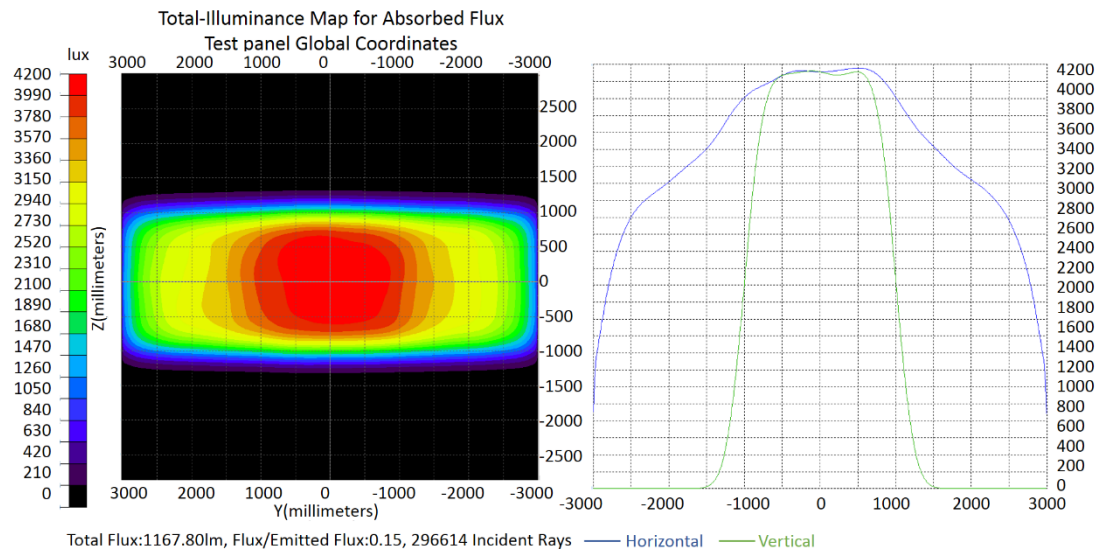


Fig 5. 15: Illuminance map of the absorbed flux of car headlamps at a distance of 100 m from the headlamps

Fig 5.15 shows the distribution of illuminance for a test panel distance of 100 m. This diagram was produced using a million tracing rays in the simulation (time: 35 seconds, computer configuration: CPU i7-4710MQ, graphics card: GTX 870M, RAM 16G). From the left-hand picture, we can clearly see that because of the energy transmission over such a long distance, the two independent faculas merged. The entire optical field distribution becomes more uniform than shown in Fig 5.14. In the right-hand picture, we can see that for long-distance energy transmission, the profiles of the horizontal and vertical illuminances become closer, unlike the profiles seen in Fig 5.14. This change also proves that long distances improve the uniformity of the optical field distribution. The next step is to obtain the average illuminance at various test-panel distances with or without a reflective sheet in the lamps.

Table 5. 3: Average illuminances at various distances from the car for headlamps without and with reflective sheets

Distance Average illuminance	0.1 m	1 m	10 m	20 m	30 m	40 m
Without reflective sheet	542.33 lx	539.00 lx	441.42 lx	417.33 lx	355.14 lx	285.02 lx
With reflective sheet	661.67 lx	628.32 lx	446.18 lx	417.33 lx	355.71lx	286.22 lx

Distance Average illuminance	50m	60 m	70 m	80 m	90 m	100 m
Without reflective sheet	237.47 lx	194.36 lx	162.02 lx	139.70 lx	116.84 lx	101.28 lx
With reflective sheet	238.37 lx	195.86 lx	163.22 lx	140.79 lx	117.81 lx	102.27 lx

Table 5.3 shows that the reflective surface can greatly improve the average illuminance for less than 10 m distance within the limited area. Table 5.3 also shows clearly that when the distance ranged from 100 m to 1 m, the illuminance changed by a factor of almost five. Because these various levels of illuminance can be directly perceived by human eyes, these data also illustrate why drivers complain about high-beam headlamps. When an oncoming car with its high-beam headlamps draws close to a driver (at the average speed of a car, only a few seconds is required to cover 100 m), the amount of light energy reaching the driver's eyes rapidly increases to five times the normal level in a few seconds. The result is instant blindness due to the oncoming light. For this reason, many countries restrict the use of high beam lamps.

5.2.3 Analyzing and improving the loss of the emitted light energy on the road

High-beam headlamps are always accompanied by a second type of headlamp known as the low-beam lamp. The significant difference between the high-beam and low-beam lamps is the working distance. Compare to the 40 m illumination distance of a low-beam lamp, a high-beam is meant to illuminate a distance of 100 m. Humans cannot distinguish the details on the ground at distances of 100m. The main function of the high-beam lamp is to detect obstacles at a certain distance above the ground, such as vehicles, people, and trees. To complement this function, the low-beam lamps provide illumination of the road for a relatively short distance. In addition, high-beam lamps also illuminate the road to a certain extent, complementing the area that the low-beam

lamps cannot reach.

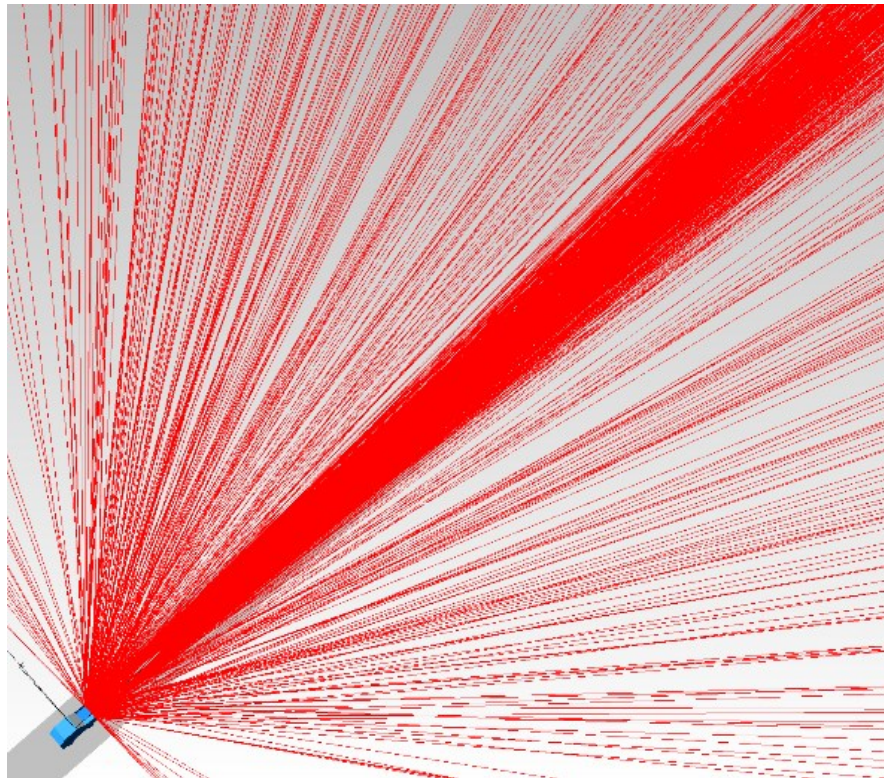


Fig 5. 16: Ray tracing from the car to the road at 100 m

Fig 5.16 shows ray tracing from the car to a test panel at 100 m distance. The range of the rays covers the road at a wide angle from short to long distances.

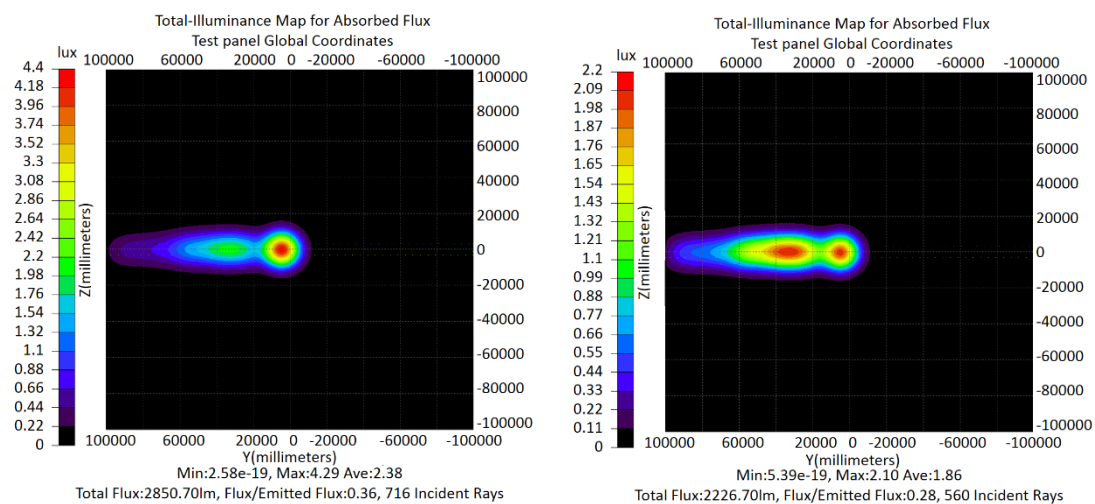


Fig 5. 17: Illuminance map of absorbed flux of the road for headlamps with and without a reflective sheet

Fig 5.17 shows the illuminance map of the absorbed flux of the road for headlamps with and without a reflective sheet. The total flux on the left side of Fig 5.17 is 2850.70 lm, which is greater than the value of 2226.30 lm seen on the right side of Fig 5.17 for lamps without the reflective sheet. In Fig 5.17, it is clear that the maximum value of illuminance is far less at the vertical test panel even though the reflective sheet greatly

enhances the illuminance from 2.20 lx to 4.40 lx. This result also illustrates that why when the high beam switch on the low beam still on working but turn off to save the power.

5.3 The effect of color temperature on light transmission under various weather conditions

5.3.1 Analysis of transmission of high beams in the mist related to color temperature

The color temperature is often used to evaluate the perception of the color of white light. Light with a color temperature above 5,000 K is referred to as having a cool color, while light whose color temperature varies from 2,700 K to 3,000 K is referred to as having a warm color.

The color temperature used for high-beam lamp ranges from 3,000 K to 6,500 K. High-beam lamps of color temperature around 4,000 K, 5,000 K, and 6,000 K [41] are most often used. In this section, we analyze the transmission of light with various color temperatures on misty days. High-beam lamps with 3,000 K and 6,500 K LEDs have been tested to evaluate the effects on our model. In addition, a 6,500 K LED provides light with the same color temperature as the standard daylight lamp D65. In comparison, 3,000 K is the lowest color temperature product used in penetrating beam lamps because it has the strongest transmission values [42].

According to the models of attenuation [43],

$$\frac{dE(x, \lambda)}{E(x, \lambda)} = -\beta(\lambda)dx \quad (1)$$

Where x is the micro distance along the light transmission path, λ is the wavelength of light, and β is the absorption or scattering coefficient of the solute.

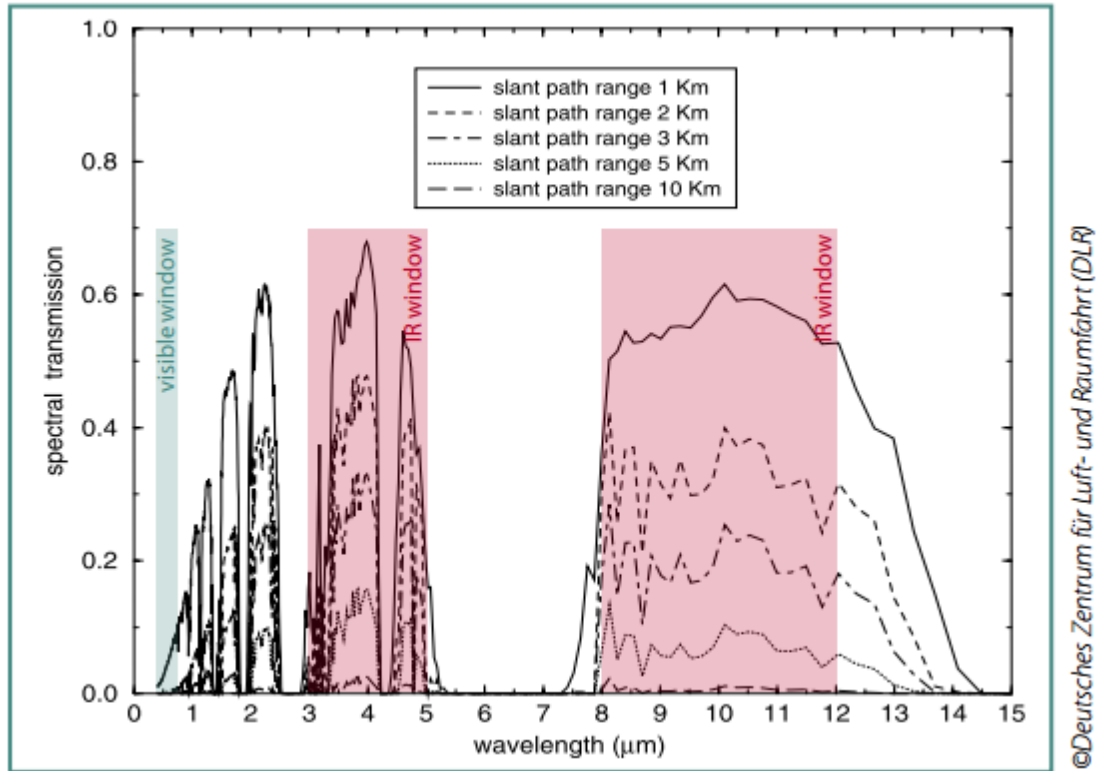
Integrating x from 0 to d , we obtain:

$$E(d, \lambda) = E_0(\lambda)e^{-\beta(\lambda)d} \quad (2)$$

Where $E_0(\lambda)$ is the original output energy. From this comes the transmission T :

$$T = \frac{E(d, \lambda)}{E_0(\lambda)} = e^{-\beta(\lambda)d} \quad (3)$$

Using a graph shared by the German Aerospace Center, we have obtained data on the spectral transmission in fog (in the presence of rural aerosols) for conditions in a middle



Temperature (K)	Wavelength (μm)	Index	Absorption [/mm]	Extinction,K [μm/μm]
6500	0.37834	1	4.8e-006	1.4451523480653e-010
6500	0.421863	1	4.6e-006	1.54425638042425e-010
6500	0.465385	1	4.099e-006	1.51803028379589e-010
6500	0.508907	1	3.799e-006	1.53850125253416e-010
6500	0.55243	1	3.4e-006	1.49467340860835e-010
6500	0.595952	1	3.201e-006	1.51805354986125e-010
6500	0.639474	1	2.9e-006	1.47574399714183e-010
6500	0.682997	1	2.7e-006	1.46748170700363e-010
6500	0.726519	1	2.5e-006	1.44536362625226e-010
6500	0.770041	1	2.4e-006	1.47066997840111e-010

Fig 5. 18: Spectral Transmission Model for mist from the German Aerospace Center, and the data calculated from the Spectral Transmission Model

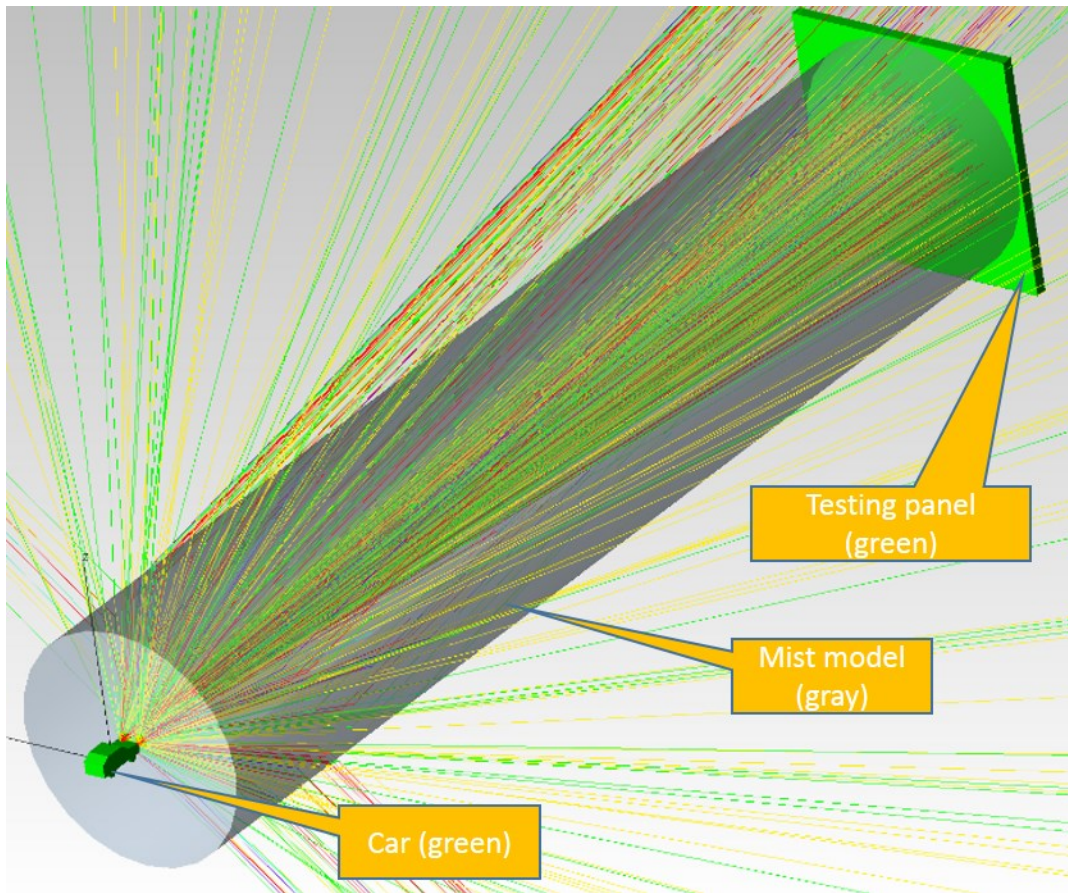


Fig 5. 19: Ray tracing from the car to the test panel

We have imported the data from Fig 5.18 to model of mist within the translucent cylinder shown in Fig 5.19. With ray tracing, the effect of high-beam lamps with 3,000 K and 6,000 K LEDs in the mist has been simulated.

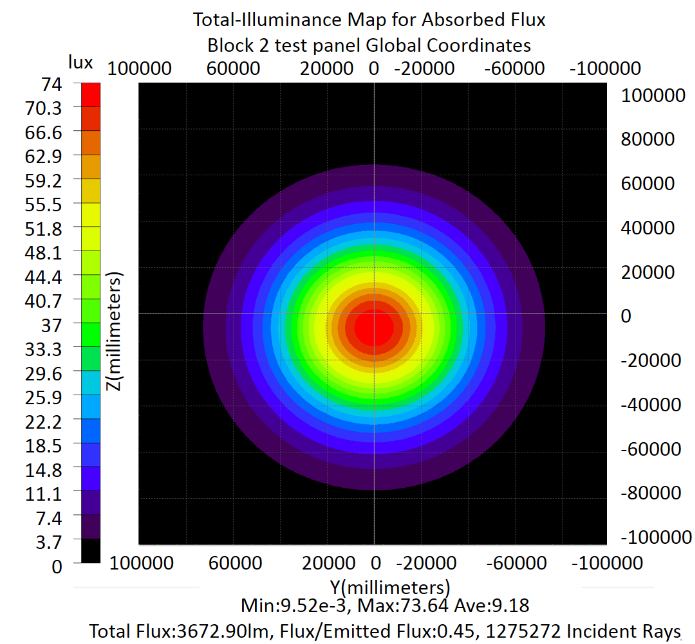


Fig 5. 20: The illuminance and color distribution of a 3,000 K high-beam lamp at 100 m distance from the car

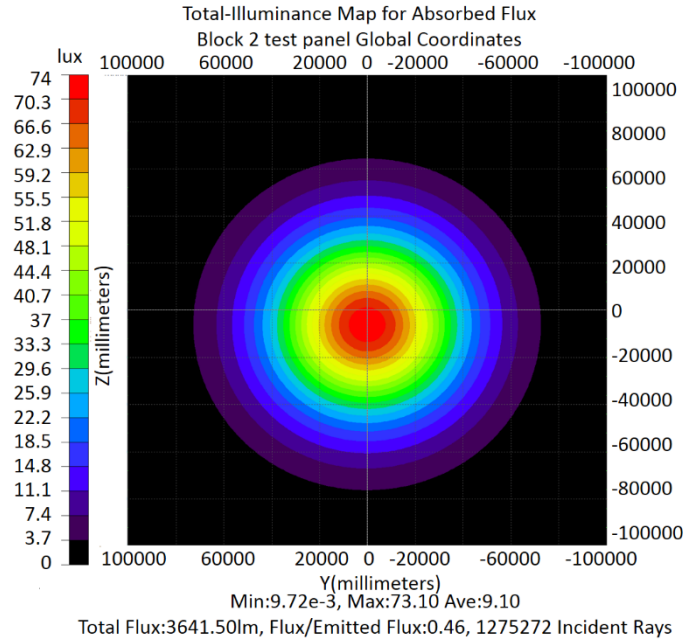


Fig 5. 21: The illuminance and color distribution of a 6,500 K high-beam lamp at 100 m distance from the car

To obtain the illuminance and color distribution, we calculated the rays that are emitted from these high beam lamps, which then pass through the mist model, and are finally received by the test panel. Figures 20 and 21 show the results for ray sources with 3,000 K and 6,500 K high-beams lamps, respectively. The total flux of the 3,000 K high beam is 3,672.90 lm while the total flux of the 6,500 K high beam is 3,641.50 lm. The values are similar. In the weather condition of mist, the warm color (3000K) which shows in Fig. 20 should have higher light transmission.

5.3.2 Analysis of transmission related to various high-beam color temperatures in fog based on the hypothesis of mist data

Because the difference in the transmission simulation results in the mist between 3,000 K and 6,500 K is small, it forces us to challenge the conventional view that the performance of low color-temperature lights is better than that of high color-temperature lights in bad weather conditions. The conclusion from simulation results is partially consistent with the experimental results mentioned in related works, specifically References [35] and [36]. In addition, a search of the documentation for high-beam lamps on the homepage of well-known lamp manufacturers such as OSRAM or Philips reveals that the parameters of transmission as determined by varying color temperatures are not mentioned at all. For this reason, we need a quantitative analysis method that uses modeling and simulation to challenge the conventional view that lamps with low color temperature perform better than lamps

with high color temperature in bad weather conditions.

Based on these reasons, we have to prove the conclusion that low color-temperature lamps perform better than high color-temperature lamps in bad weather conditions. The data shown in Fig 5.19 from the German Aerospace Center indicate that the maximum spectral transmission of visible light is approximately 0.1 per kilometer, which means the energy drops to 10 percent in the distance of 1 km. We assumed that the light transmission in the mist is 10 times as great as in the fog based on the fact that visibility in fog is far less than visibility in mist. Therefore, we adjusted the transmission of 0.1 per kilometer into 0.1 per hundred meters and imported it into the models of attenuation.

Temperature (K)	Wavelength (μm)	Index	Absorption [/mm]	Extinction, K [μm/μm]
6500	0.37834	1	4.8e-005	1.4451523480653e-009
6500	0.421863	1	4.6e-005	1.54425638042425e-009
6500	0.465385	1	4.099e-005	1.51803028379589e-009
6500	0.508907	1	3.799e-005	1.53850125253416e-009
6500	0.55243	1	3.4e-005	1.49467340860835e-009
6500	0.595952	1	3.201e-005	1.51805354986125e-009
6500	0.639474	1	2.9e-005	1.47574399714183e-009
6500	0.682997	1	2.7e-005	1.46748170700363e-009
6500	0.726519	1	2.5e-005	1.44536362625226e-009
6500	0.770041	1	2.4e-005	1.47066997840111e-009

Fig 5. 22: Assumed spectral attenuation model in fog and the parameter settings for transmission

With reference to the spectral attenuation model for mist, we simulated the data for fog and imported the data into the new model as shown in Fig 5.22.

Table 5. 4: Luminous flux for double color-temperature high beams at various distances from the car

Distance Luminous Flux	100 m	90 m	80 m	70 m	60 m	50 m	40 m
6,500 K	3.16 lm	153.13 lm	327.98 lm	472.53 lm	671.08 lm	947.28 lm	1343.20 lm
3,000 K	7.83 lm	199.40 lm	355.31 lm	504.96 lm	706.38 lm	988.68 lm	1390.00 lm

Table 5.4 shows the test results for luminous flux at various distances related with double color-temperature high beams that share the same model as was used for Fig 5.19. Based on the results in Table 5.4, the largest difference occurs at greater than 90 m, in particular at 100 m, which means that above a certain distance, a 3,000 K high-beam lamp is actually more effective than a 6500 K high-beam lamp.

We next imported the model used for Fig 5.13 into this spectral-attenuation model to test the average illuminance at various distance for a car with double color-temperature high beams.

Table 5. 5: Average illuminance for a car with double color-temperature high-beam lamps at various distances

Distance Average illuminance	100 m	90 m	80 m	70 m	60 m	50 m	40 m
6,500 K	0.06 lx	3.52 lx	8.83 lx	15.07 lx	25.57 lx	43.13 lx	72.94 lx
3,000 K	0.15 lx	4.57 lx	9.56 lx	16.09 lx	26.89 lx	44.97 lx	75.43 lx

The values for average illuminance presented in Table 5.5 invite a similar conclusion to that drawn from Table 5.4. Meanwhile, based on the results of Table 4, it can be seen that the differences between the two test results at 3,000 K and 6,500 K are approximately constant for distances less than 90 m. However, due to the increments in luminous flux as the illumination distance decreases, the ratio of this approximately constant to luminous flux are getting smaller.

5.3.3 New proposal for double color-temperature high-beam lamps

As more and more LEDs are used in high-beam lamps, the advantage of LEDs with their low driving voltage and small package can change the traditional use of single color-temperature high-beam lamps.

In this paper, we propose a new model that involves LEDs with two different color temperatures in each high-beam lamp that can be switched on or off by rotation to accommodate various weather conditions.

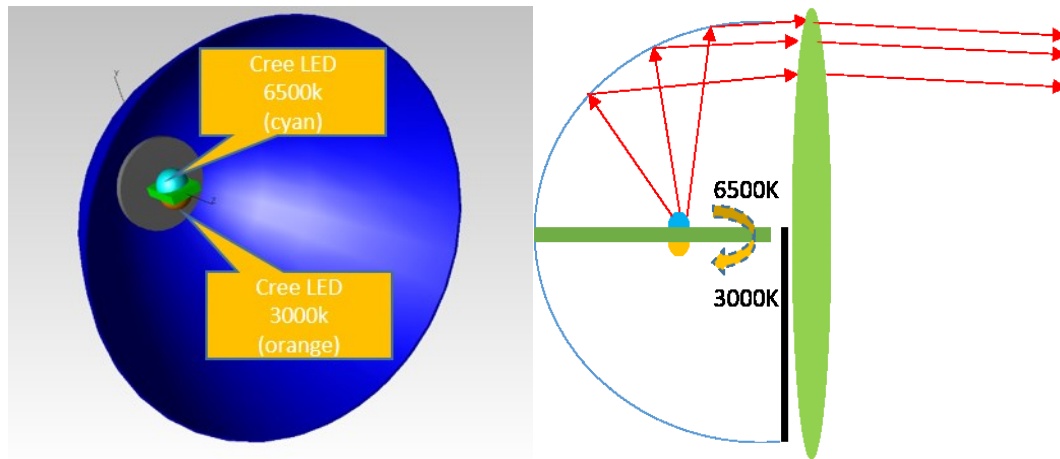


Fig 5. 23: The model and diagram for a double color-temperature high-beam lamp

The LED lamp used in Fig 5.18 is a Cree XLamp XHP70, which has a powerful output and provides light at two color temperatures (6,500 K and 3,000 K). The right-hand picture in Fig 5.23 is the lighting configuration that is widely used in xenon lamps. Furthermore, in recent years, this optical design has also been used in a single side-emitting LED car lamp such as the Cree XLamp XHP70 [38].

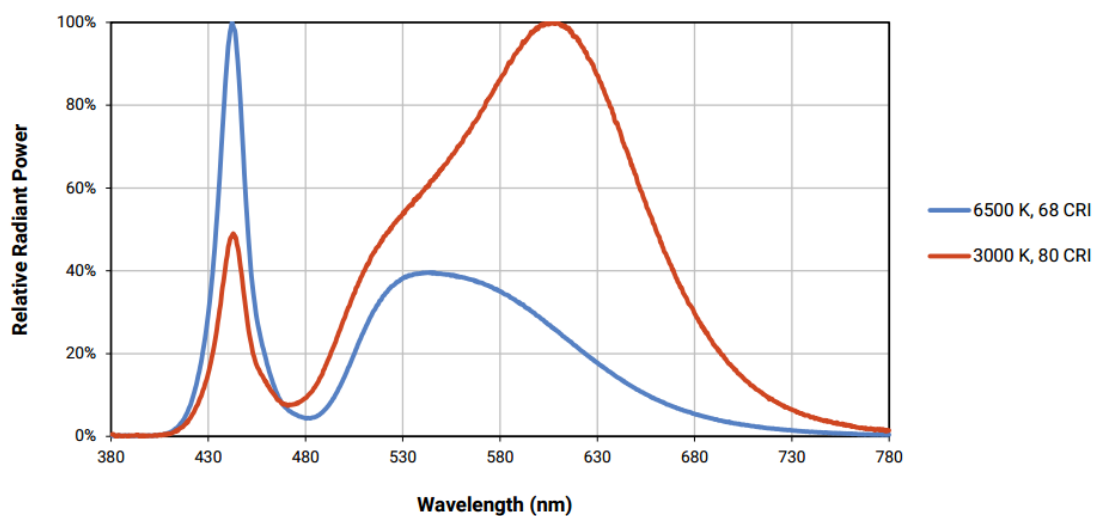


Fig 5. 24: The spectrum distribution of the Cree XLamp XHP70 from the CREE Company

The color temperatures of 6,500 K and 3,000 K are the ones we have analyzed in the Spectral Transmission Model. Fig 5.24 shows the spectrum distribution of a high-power LED that has been developed by the CREE Company. If a car is being driven in good weather at night, the 6,500 K high beam lamp can be used. However, if the weather changes into mist, fog, or heavy rain during the night, the 3,000 K LED can be switched on by rotating the base by 180 degrees.

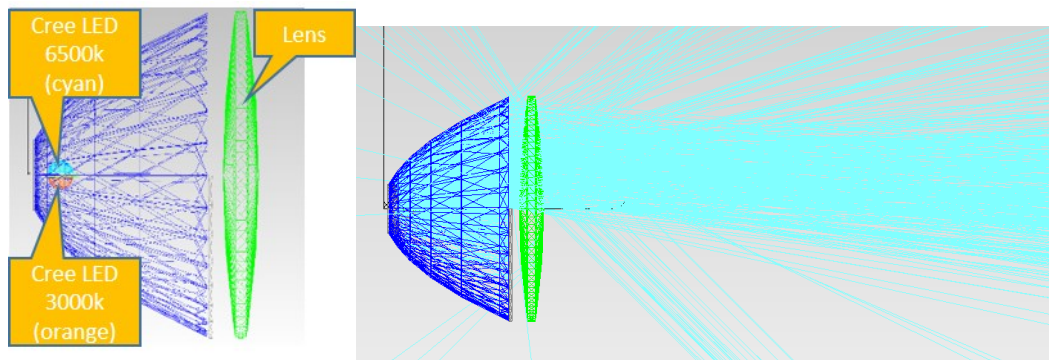


Fig 5. 25: Perspective drawing of rotatable high-beam lamp and ray-tracing results

On the right side of Fig 5.25, the results of ray tracing for the rotatable high-beam lamp are shown. From the shape of the tracing rays, the amount of diffusion is not significant, and this lamp, when used as a high-beam lamp can provide illumination over great distances.

This new proposal of double color-temperature high-beam lamps are mainly based on the research of section 5.3 “The effect of color temperature on light transmission under various weather conditions”. Section 5.3 proved that low color temperature lamps (3000K) have better transmission than high color temperature lamps (6500K) in some low visibility weather conditions, so under normal circumstances we should choose low color temperature lamps as high beam lamps for automobiles. Yet on the contrary, it is high color temperature lamps that have been chosen by almost all premium carmakers owing to their better color performance, brightness and fashionable design. Meanwhile based on the law of $E=h\nu$, except the case under some specific weather conditions of attenuation, high color temperature lamps should have better transmission than low color temperature lamps in normal weather conditions. To solve this contradiction, this new model of double color-temperature high-beam lamps has been proposed and briefly verified.

5.4 Result

By investigating the luminous flux received at various distances with and without a reflective sheet behind the lamp, we have concluded that the effect of the reflective sheet decreases with an increase in distance. However, the reflective sheet improves the performance at distances between 0 and 30 m. We then simulated the installation of two high-beam lamps at the same distance apart as they would be in a car to test the energy efficiency in a real environment. Luminous flux was calculated and illuminance was

also evaluated for the same situation. The result shows that the reflective sheet improves performance for less than 10 m distance in both the luminance flux test and the illuminance test. In addition, because a large part of light energy is emitted in the direction of the base, heat accumulates in this area and causes a temperature rise. Therefore, the reflective sheet not only improves the efficiency of the output but also decreases heat accumulation.

The next experiment analyzed the effect of different color temperatures on light transmission. According to the correlated color temperature contrast, we have concluded that the transmission of high-beam lamps emitting light with color temperatures of 3,000 K and 6,500 K is almost the same under weather conditions of mist. However, under other weather condition such as fog or rain, because the water vapor particles and dust are of greater size and higher density than those of mist, the effect of diffraction at different wavelengths will become greater. Accordingly, the transmission of these two color temperature lamps may be different if the 3,000 K high-beam lamp performs better than the 6,500 K high-beam lamp. Based on this hypothesis, we assumed that the light transmission in fog is 10 percent of that in mist. By using this assumed data, we analyzed the transmission performance of two color-temperature high-beam lamps at various distances to determine the luminous flux and average illuminance. The result showed that for a long distance, the 3,000 K high-beam lamp performed better than did the 6,500K lamp. Furthermore, the results of luminous flux testing show that for a significant distance in front of the car, the light transmission of the 3,000 K high-beam lamp is significantly higher than that of the 6,500 K lamp. This conclusion not only indicates that a driver who uses high-beam lamps to illuminate the area in front of him in bad weather conditions will benefit, but also others would be warned by seeing the light from high beam lamps in low visibility weather conditions.

Finally, we proposed a new rotatable double color-temperature high-beam lamp that is used to solve the contradictions of high transmission in bad weather and good color performance in good weather.

Chapter 6 Scalable LED Import into Headlight Lamp of Automobiles

6.1 Background

Based on the research of headlight lamp of automobiles described previously, we can infer that if the high beam lamp is used in low visibility weather conditions, its illumination effectiveness will be greatly decreased due to the fact that the absorption and scattering of particles in the air have huge impact on visible light.

Many automobiles have been used in the area with low visibility weather condition all the year round. Under this circumstance, more powerful high beam lamps are in need. However, XHP70 with 4022lm output is currently the largest luminous flux product in the LED market. Some other types of high output lamp also exist, however the life time is extremely short compared with LED such as high-voltage mercury lamp mostly used as light source in projector. Meanwhile the output of luminous flux from other traditional light sources for high beam lamp is even lower than that of LED, less than 4022lm per lamp for halogen lamp and xenon lamp. Then judging from the simulation result of Table 5, we can conclude that even high beam lamp with high LED reaches a high output of 4022lm per lamp. The illumination drops to 25lx at the distance of 60m, meanwhile 20lx is the lowest illumination value which allows human beings to recognize objects. Therefore we have to further improve the output of high beam lamp to meet the demand of usage in some extreme weather conditions, such as fog, rain and blizzard.

6.2 High beam lamp with high output

6.2.1 Improvement of output of high beam lamp by increasing the number of LED

In order to solve this problem, we have to increase the output of high beam lamps. And naturally the first tentative solution is to increase the number of LED in the original lamp, shown as Fig 6. 1.

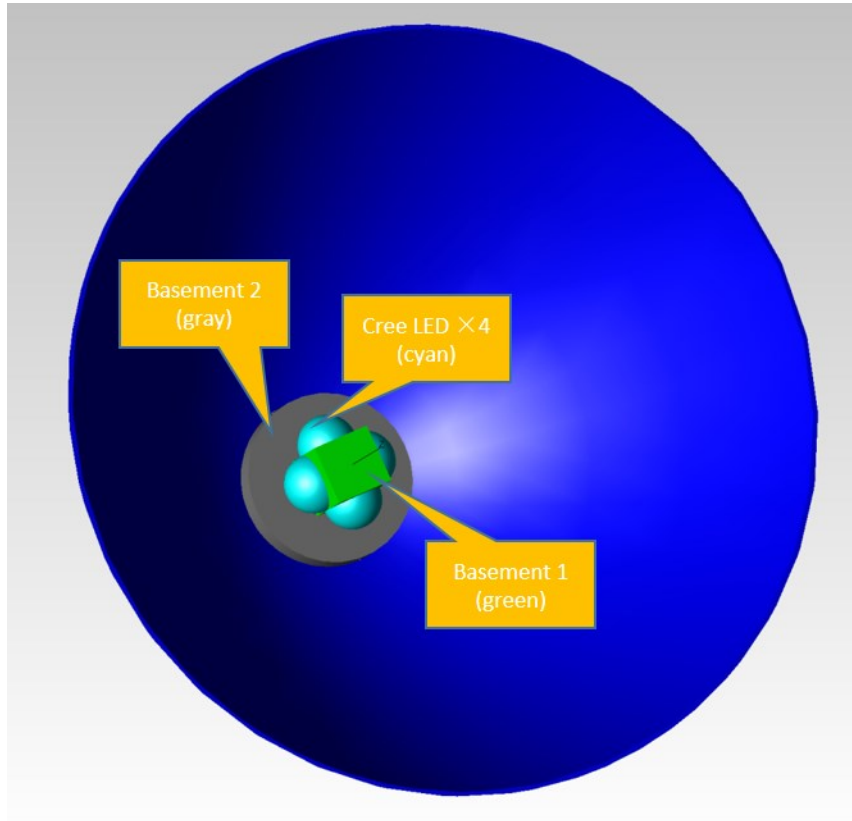


Fig 6. 1: Model of an integrated high-beam lamp with 4 high output XHP70 LEDs

Considering that the focus point of reflector is fixed and unique, the model shown in Fig 6.1 is the most reasonable construction which is used to improve the output of high beam. In Fig 6.1, 4 high output XHP70 LEDs, set around the focus point of reflector, have been used in this model. Certainly more than 4 LEDs can be also set at the basement by increasing the size of basement in this model. However with the number of LED increases, the distance between the LED and focus point of reflector also increases. As the distance increases, the efficiency of reflector decreases, which can be proved by comparing the two models with 2 and 4 LEDs respectively.

The model shown in Fig 5.23 with double color temperature high beam lamp using 2 LEDs is used to compare the optical efficiency with the model shown in Fig 6. 1 with 4 LEDs. By introducing these two different numbers of lamps into the model of car and setting a test panel the same size with that shown in table 5 (6m×2m) at the distance of 50m, the illuminance map can be presented in Fig 6. 2 and Fig 6.3.

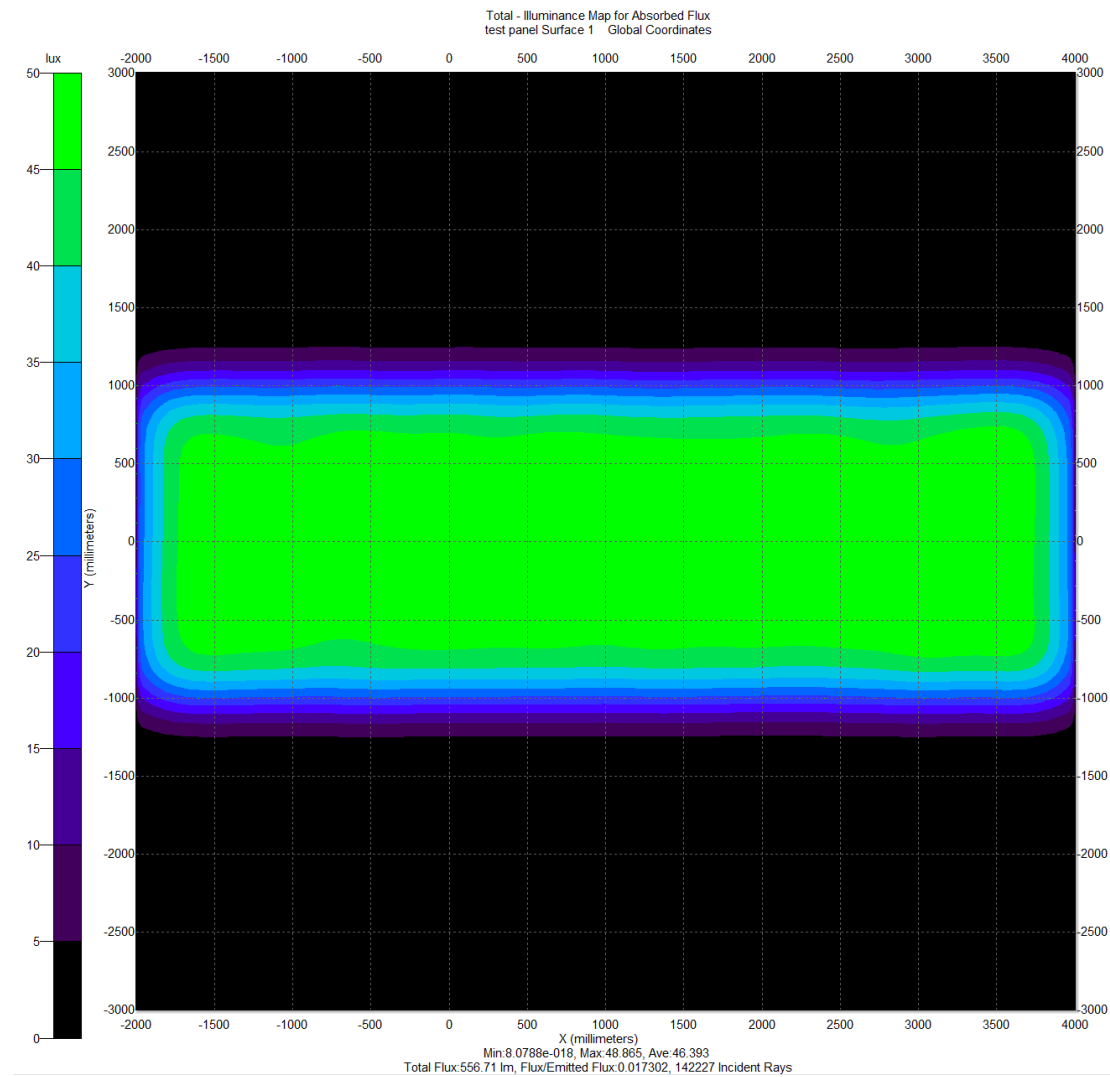


Fig 6. 2: Illuminance map of the absorbed flux of car headlamps at a distance of 50m from the headlamps with 4 high output XHP70 LEDs

Fig 6.2 demonstrates the illuminance map of the absorbed flux of car headlamps at a distance of 50m from the high beam lamp with 4 high output XHP70 LEDs. The number of tracing rays is a million. Meanwhile, according to the illumination of light source using 4 LEDs per lamp, the distribution of illuminance map is perfectly uniform.

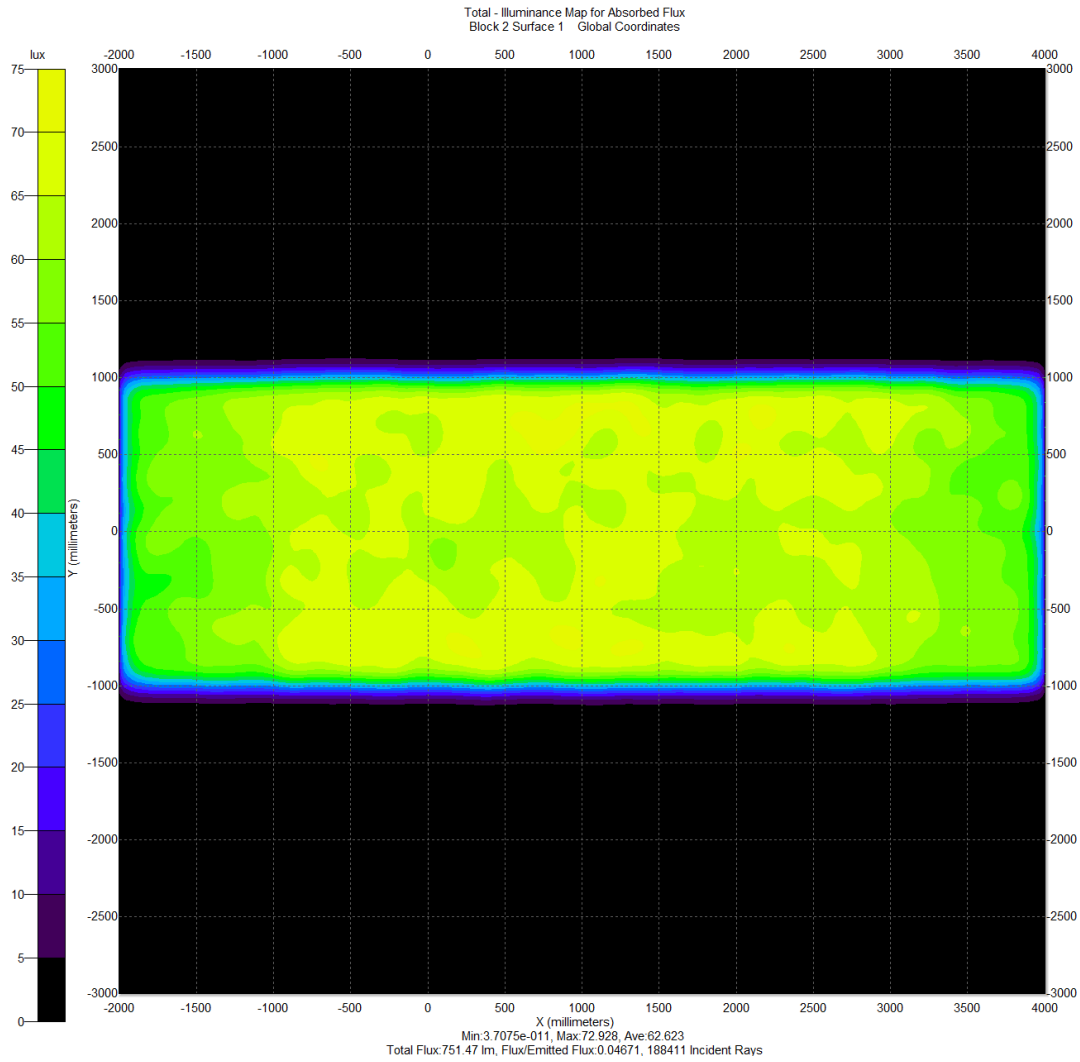


Fig 6. 3: Illuminance map of the absorbed flux of car headlamps at a distance of 50m from the headlamps with 2 high output XHP70 LEDs

Fig 6.3 presents the illuminance map of the absorbed flux of car headlamps at a distance of 50m from the high beam lamp with 2 high output XHP70 LEDs. And the number of tracing rays is also a million. Compared with the distribution of illuminance map in Fig 6.2, the uniformity of illuminance map in Figure 6.3 is less than that shown in Fig 6.2 in that fewer LEDs per lamp have been used.

However, the simulation result of two headlamps yields a conclusion opposite to traditional concept. The average illumination of high beam with 4 LEDs per lamp is 46.39lx while that of the high beam with 2 LEDs per lamp is 62.62lx. Meanwhile, the total flux of high beam with 4 LEDs per lamp is 556.71lm which is also less than that of high beam with 2 LEDs per lamp (751.47lm). As to the number of LED, the number of LED shown in the model of Fig 6.2, which is 4, doubles that shown in the model of Fig 6.3. Although the percentage of energy loss of model in Fig 6.2 is larger than that of the model in Fig 6.3 because the distance between LED and focus point of reflector

is a little further than model in Fig 6.3 (The different is 3mm according to calculation), the total flux and average illumination of the model in Fig 6.2 should be larger than that of the model in Fig 6.3 considering that the original output of the model in Fig 6.2 doubles that of the model in Fig 6.3.

According to the conclusion from this experiment, there is no point in insisting on improving the output of high beam lamps by just adding the number of LED on the basis of the original structure of high beam lamps.

6.2.2 Ultra-high output high beam lamp with multiple-layer LED backlighting structure

The experiment above proved that simply increasing the number of LED in the conventional model cannot improve the output of high beam lamps. Based on this conclusion, we have to resort to other strategies in order to improve the output of high beam. The proposal of multiple-layer LED backlighting structure in Chapter 3 can be ?
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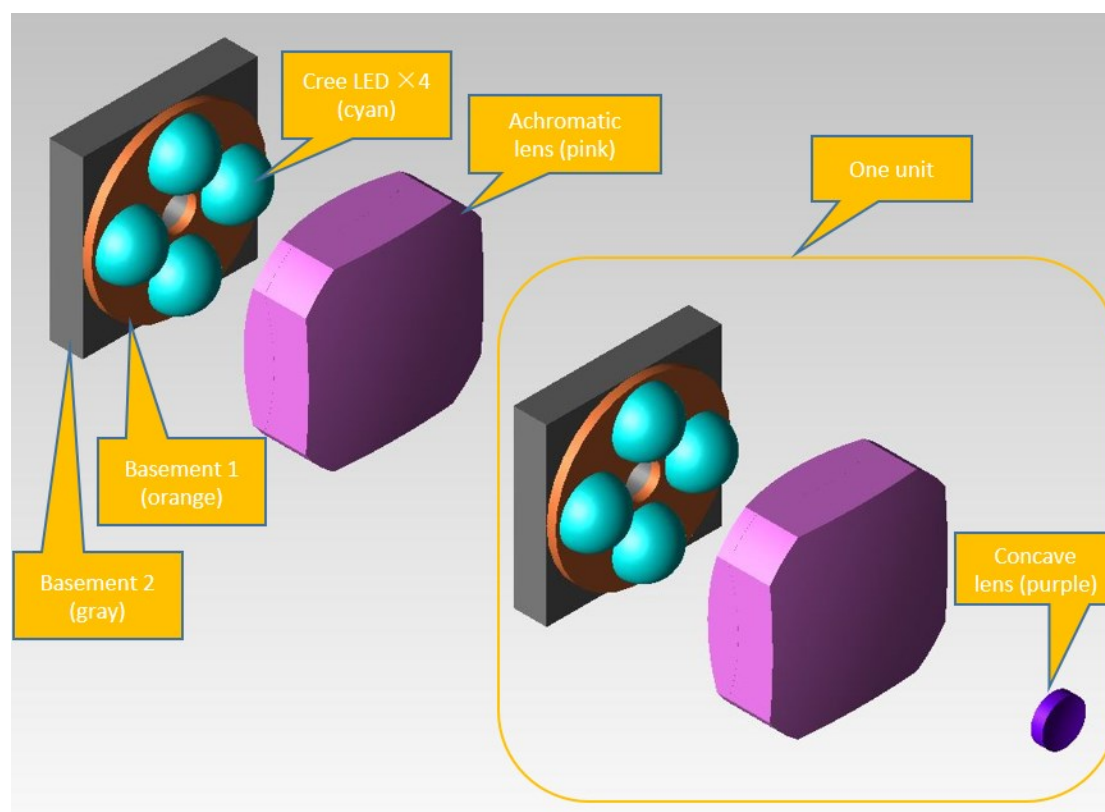


Fig 6. 4: High beam lamp with multiple layers LED backlighting structure used in this case

Fig 6.4 shows high beam lamp with two layers of LED based on simplified multiple backlighting structure. The LED used in this model is XHP70, the same as the LED used in conventional high beam lamps. The multiple-layer LED illuminance model differs from the DIP LED model in Fig 6.5 in Chapter 3 not only in terms of the types of LED but also the availability of Fresnel lens.

The model in Fig 6.4 is based on a hypothesis of collimated light from XHP70 LED. The light-emitting angle of XHP70 LED is 120 degrees. In Chapter 3, we have discussed the issue of light-emitting angle from LED. The reason why we use DIP LED in Chapter 3 is that 120-degree light-emitting angle cannot be changed into collimated light. For the purpose of making a comparison with the conventional model of high beam lamp, we have to suppose that the light from XHP70 LED is collimated light. Therefore Fresnel lens have been canceled based on this hypothesis.

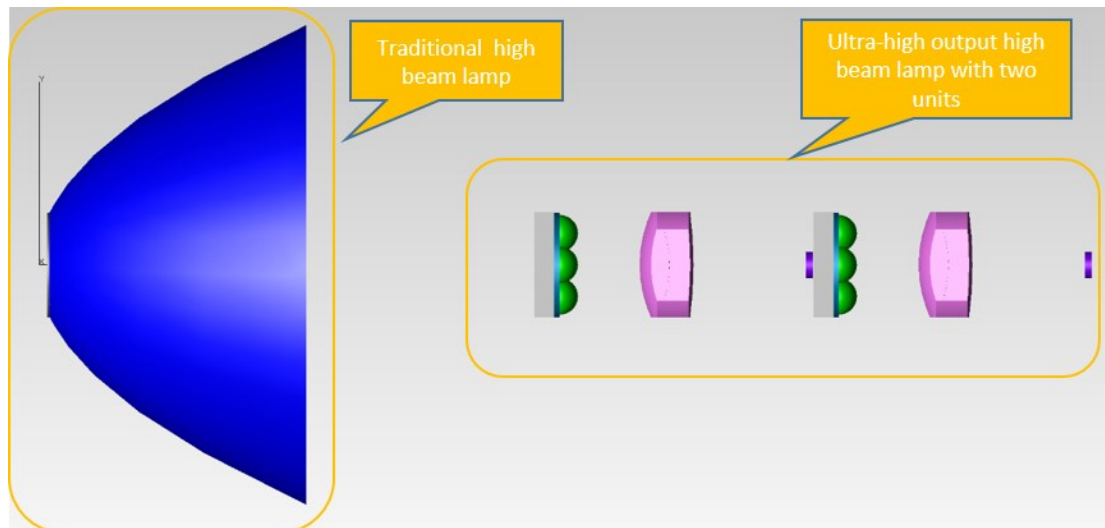


Fig 6. 5: High beam lamp with multiple layers LED backlighting structure and conventional high beam lamp

Fig 6.5 shows the size of multiple-layer LED high beam lamp and conventional high beam lamp. Based on this small size, the two layers of LED high beam lamp can be combined into a large model: 4 units of two layers of LED high beam lamp.

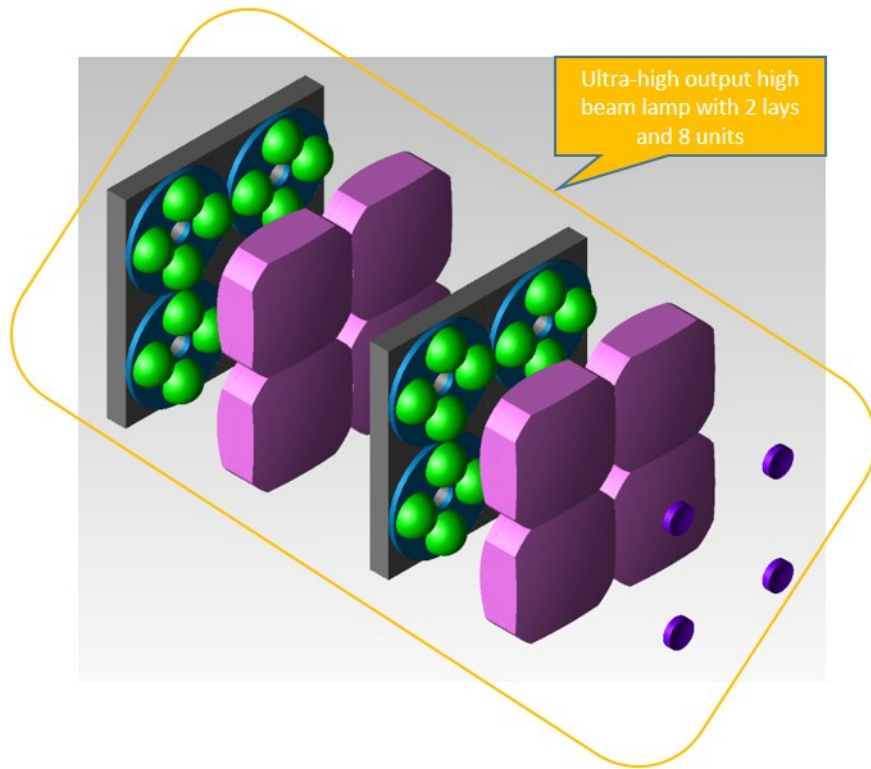


Fig 6. 6: 4 units of two layers of LED high beam lamp

Fig 6.6 shows 4 units of two layers of LED high beam lamp using 32 LEDs, which were later on installed into a car model.

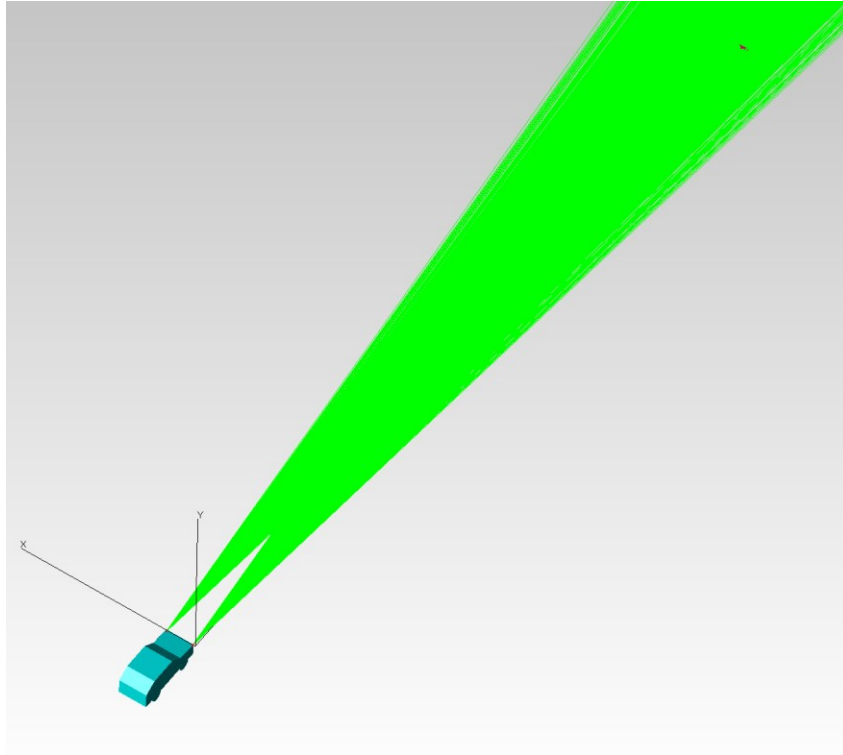


Fig 6. 7: Ray tracing from the car installed 4 units of two layers of LED high beam lamp

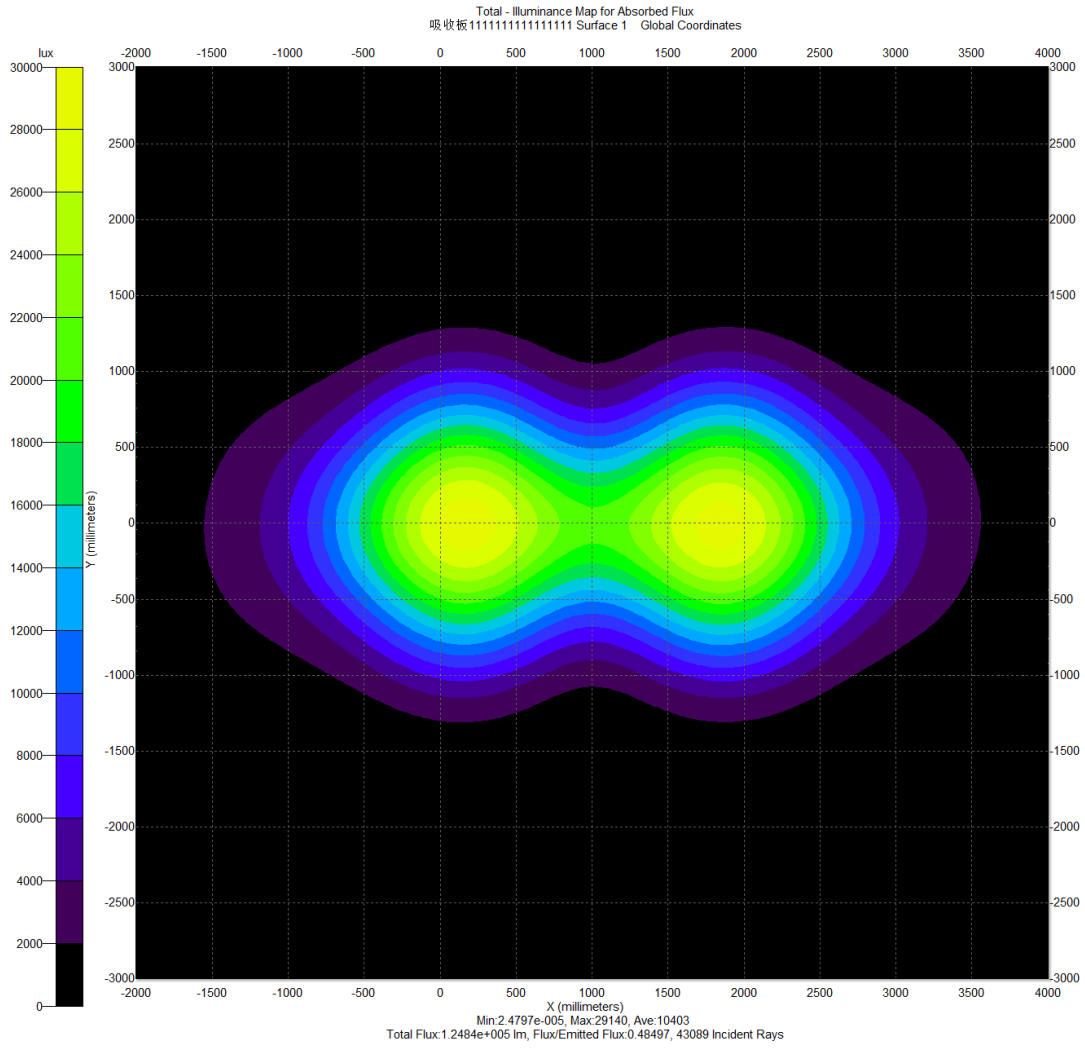


Fig 6. 8: Illuminance map of the absorbed flux of car headlamps at a distance of 50m from the two layers of LED headlamps with 32 high output XHP70 LEDs per lamp

Under the same experimental conditions, compared with the simulation in Fig 6.3, the illuminance map from Fig 6.8 based on ray tracing simulation of Fig 6.6 shows the ultra-high output of total flux and average illumination value. The total flux shown in Fig 6.8 is 124840lm and the average illumination is 10403lx. Considering the number of LED in the model of Fig 6.8 is 64 which is 16 times of that in the model of Fig 6.3, the total flux and average illumination should also be 16 times of that in Fig 6.3. Under the calculation of these values, the total flux and average illumination are somewhat larger than 16 times of the simulation result from Fig 6.3. Then we will test these values in the distance of 100m. Meanwhile the size of this ultra-high output high beam lamp is the same as that of the conventional high beam lamp.

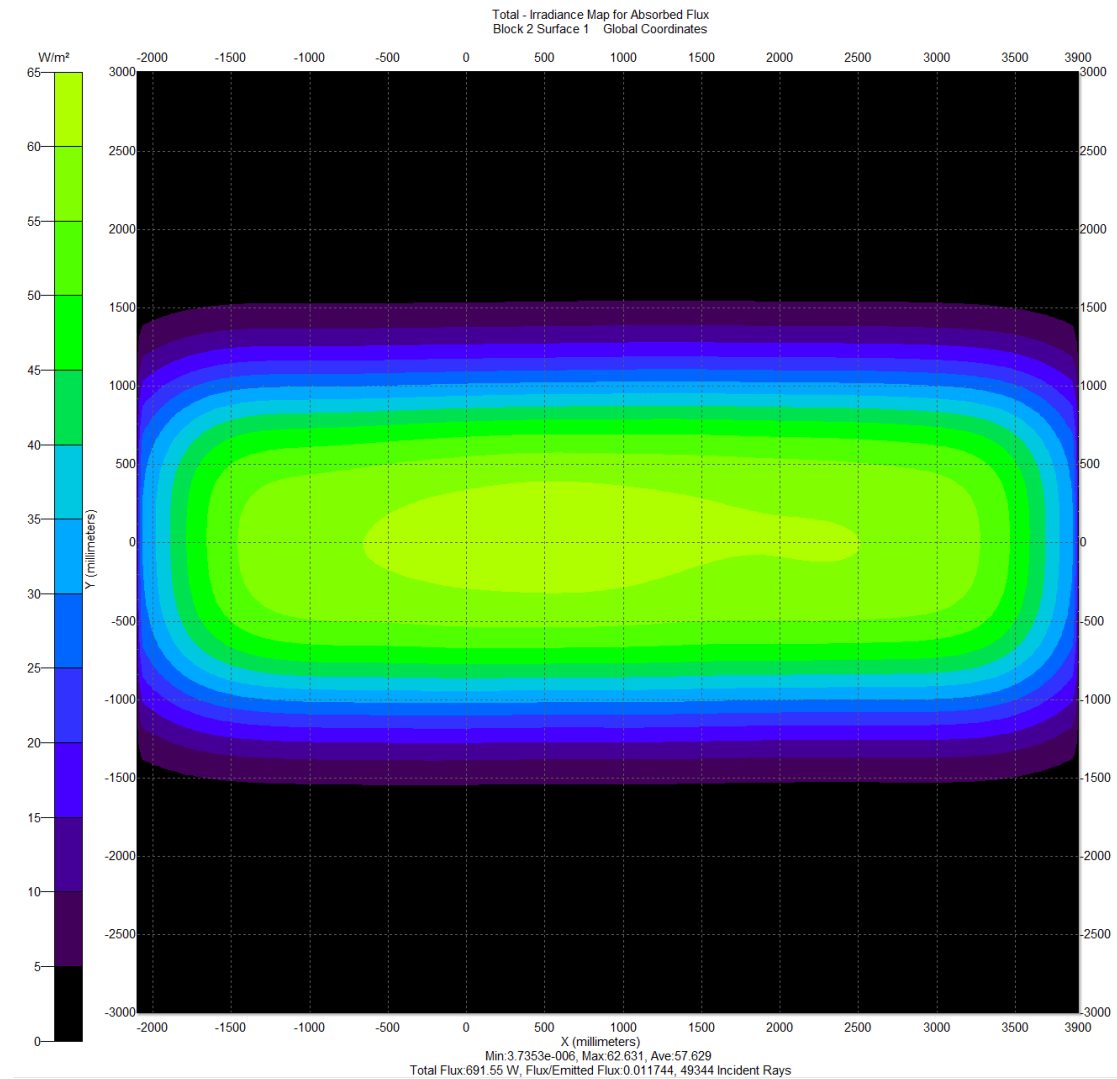


Fig 6. 9: Illuminance map of the absorbed flux of car headlamps at a distance of 100m from the headlamps with 4 high output XHP70 LEDs

From the average illumination value of table 3 in Chapter 6, the average illumination is 101.28lx at the distance of 100m. However the average illumination shown in Fig 6.9 with two LEDs per lamp is 57.63lx, which is even smaller than that with single LED per lamp.

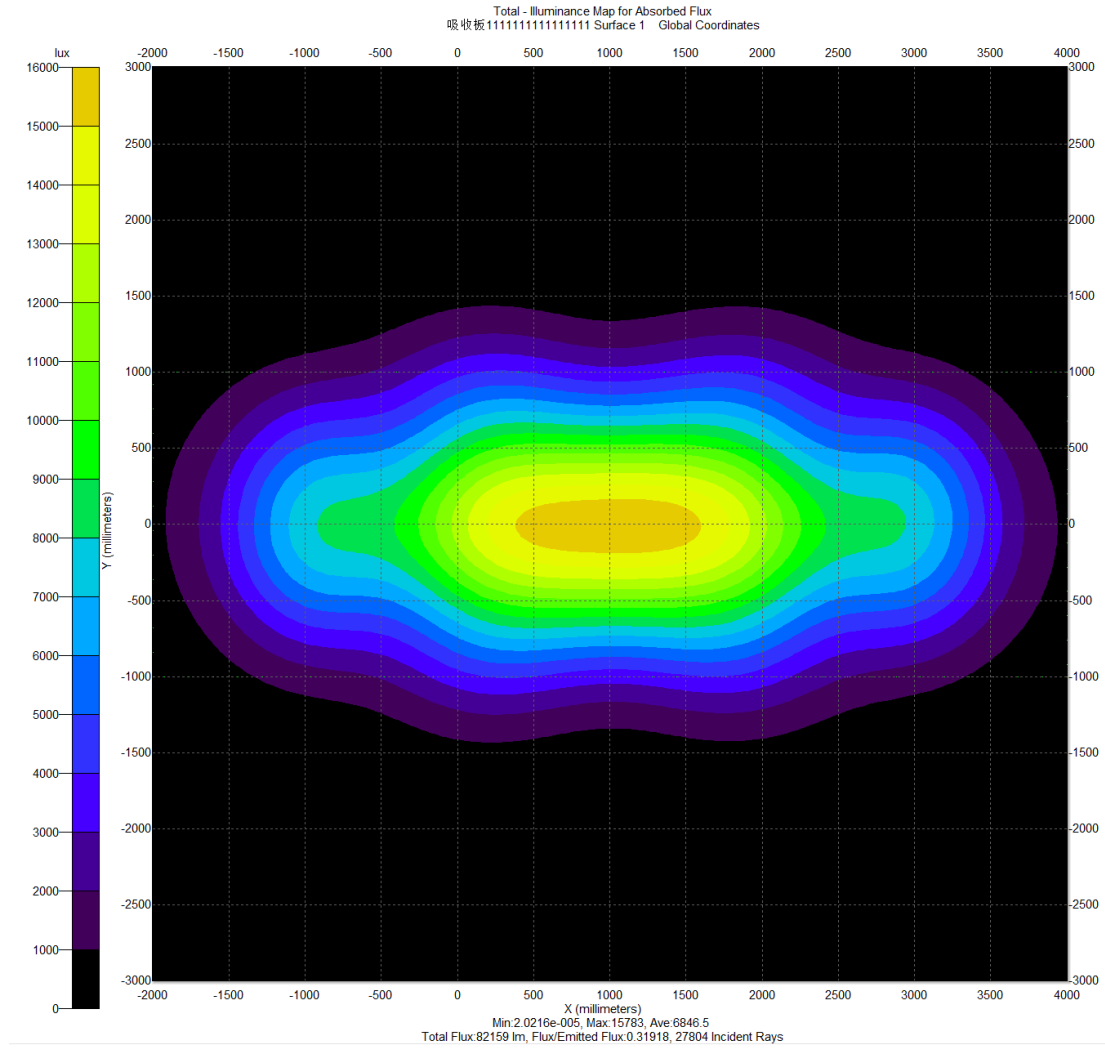


Fig 6. 10: Illuminance map of the absorbed flux of car headlamps at a distance of 100m from the two layers of LED headlamps with 32 high output XHP70 LEDs per lamp

Comparing the simulation of illumination at the distance of 100m using conventional high beam lamp shown in Fig 6.9 and the new model of multiple-layer LED high beam lamp in Fig 6.10, the result shows that the difference of total flux and average illumination at the distance of 100m are even larger than that at the distance of 50m.

Then to illustrate the effect of this ultra-high output high beam lamp, this new model will also be tested in the light attenuation model of fog.

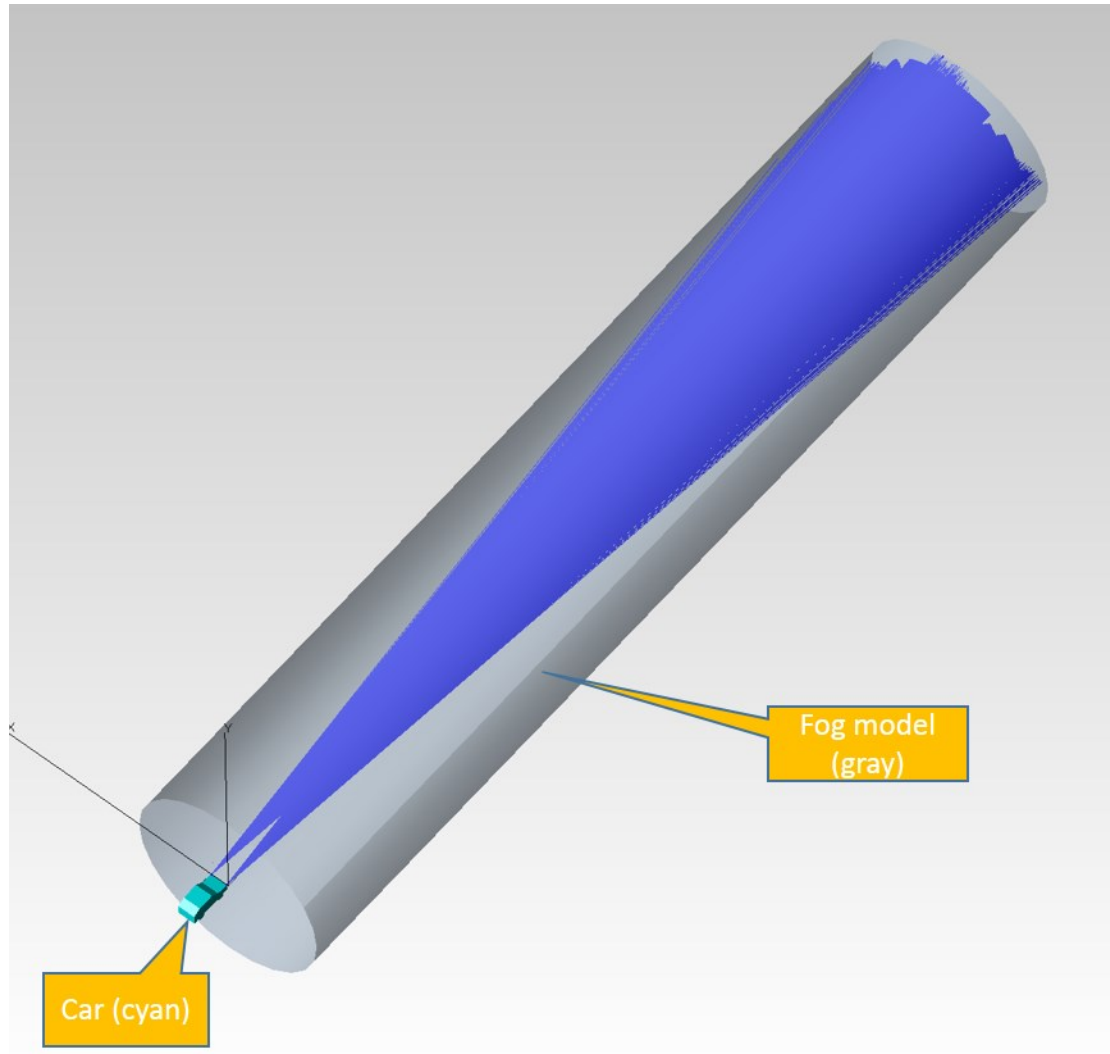


Fig 6. 11: Ray tracing from the car to the test panel in the light attenuation model of fog using ultra-high output high beam lamp

The cylinder used in Fig 6.11 presents the light attenuation model of fog which has been proposed in Chapter 5. However, the light used in the ultra-high output high beam lamp is single wavelength of 541nm which is in the middle of visible spectrum in that the experiment in this chapter is not used to analyze the color temperature of high beam lamp. Meanwhile since the white light with the whole spectrum of visible light is also combined with the parameter of light emitting angle of LED, the beam from LED here has been set as the collimated light.

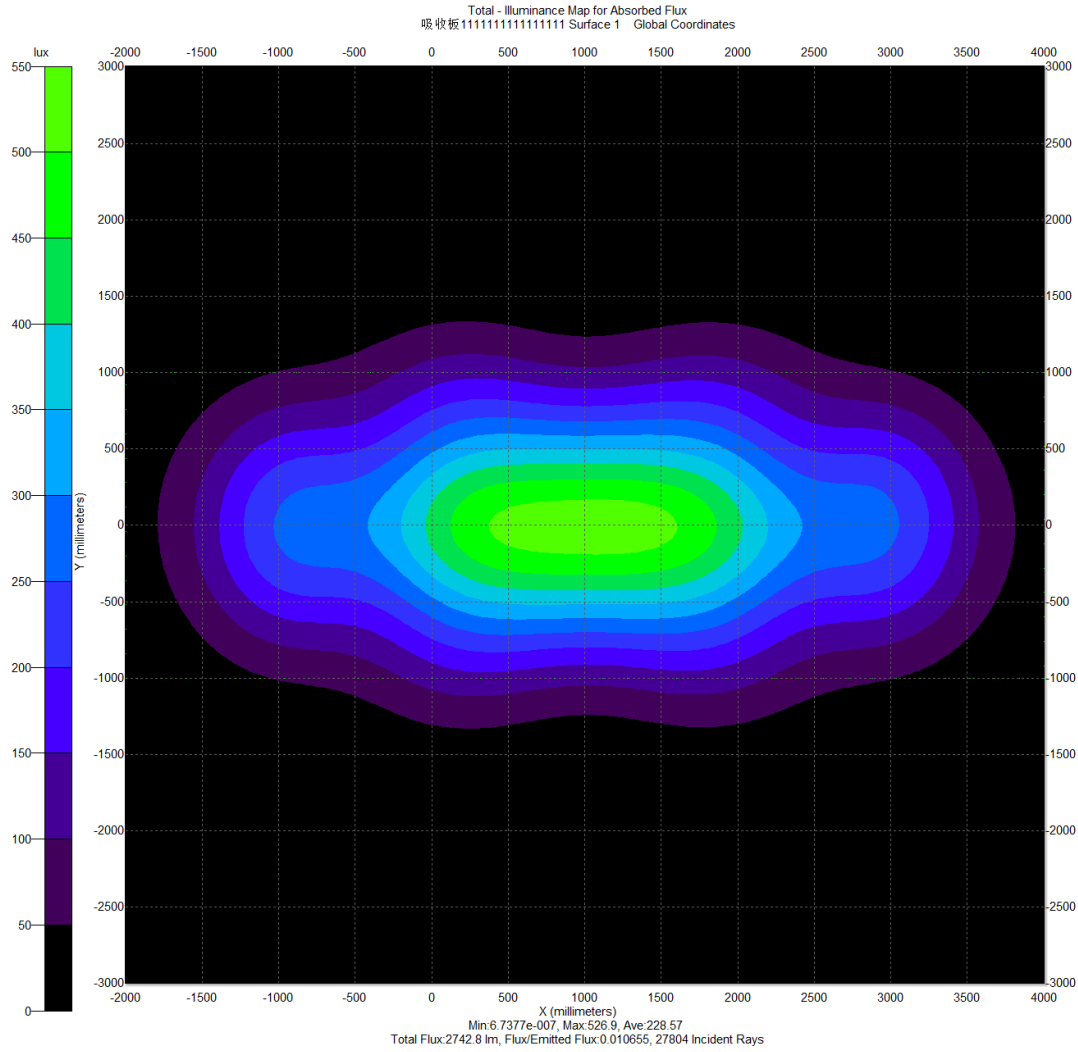


Fig 6. 12: Illuminance map of the test panel in the light attenuation model of fog using ultra-high output high beam lamp

The simulation result shows that the total flux is 2742.80lm and the average illumination is 228.57lx in Fig 6.12. The value of average illumination is even larger than that under normal weather conditions without light attenuation shown in table 3 (101.28lx at 100m). Considering that the minimum illumination human beings can recognize is 20 lx, it is conclusive that this ultra-high output high beam lamp can work well even in some extreme weather conditions such as blizzard or strong haze based on these simulations.

6.2 Conclusion

In this paper, we import the technique of multiple layers of backlighting system into the research of high beam lamp. Based on the research of light attenuation model in high beam lamp in low visibility weather conditions, ultra-high output high beam lamp is a valuable proposal to solve the problem of automobile driving in these weather

conditions. Ultra-high output high beam lamp can not only be applied in moderately foggy or rainy days but also in blizzard weather conditions even in high-latitude countries or regions covered with snow and suffering from blizzard regularly.

Due to the valuable integration of the two researches and successful simulation results, the technique of multiple layers of illumination system is considered to be useful not only in the field of headlamp lamps but also in many other fields demanding compact and high output, such as light source of projectors.

Nevertheless, a lot of work is still in progress, one of which is that the different light attenuation models have not been analyzed yet. Since light attenuation model differs in different weather conditions, the transmission of light shall be altered to a great extent based on this reason accordingly. Apart from that, the human factor has not yet been evaluated. Considering that the output of this new lamp is ultra-high, the blue light hazard is also huge especially when the ultra-high output high beam lamp adopts high color temperature light. All these studies will be continued in the future.

Chapter 7 Conclusion & Future work

With the development of technology, a growing number of people have become aware of the concept of people-oriented science and technology, the concept of which is exactly the starting point of this research. Based on the high performance, we proposed a multilayered illumination model combined with LEDs, which are an advanced light source. The model of a multiple layer illumination system can be applied in many fields, such as in the backlighting systems and headlamps of automobiles. Meanwhile, in terms of photobiology safety, some research states that the hazard from blue light may impair our eyes, which are the most important organ that humans rely on to obtain information. However, by simply reducing the blue parts of the light to remove the blue light hazard is bound to break the balance of color performance. This paper proposed a new integrated LED light source that adds a cyan LED to conventional white LEDs to solve this problem.

Regarding the techniques for the multiple layers of the illumination model, LEDs are not the only light source that can be adopted for this model. Some other new types of light sources have proved suitable, such as lasers (especially semiconductor lasers) and OLEDs. The most obvious advantage of this model is the small package. The structure of this type of innovation can make the conventional opaque basement of LEDs become transparent in some ways. An extremely high output can be achieved by using the rear space behind the conventional opaque basement. The layers can be stacked one by one in accordance with our needs, and the area of the lamp can be changed with the free combination of LED units. Furthermore, the sharpness of the beam from the lamp can also be shifted easily by replacing the small concave lens at the last layer of output. The first experiment included multiple layers of the illumination model used in a backlighting system. Regardless of the 3D TV developed by MIT or the extremely high performance HDR TV developed by SONY (Z9D), a high output backlighting system is needed. The conventional backlighting structure cannot meet the demands anymore. Our proposal, when enhanced, may become the most suitable solution. However, this compact structure can also be used in headlamps and projectors that require a high output because the light-emitting area is strictly restricted. From the traditional understanding, a high output of light means increasing the light-emitting area or sharply decreasing the lifetime of the light source. A searchlight requires the former, whereas a projector requires the latter. However, our proposal of a multiple layered illumination model overcomes the drawbacks of the old concept. We determined the feasibility of

the model that significantly improves the output of high beam lamps by importing this model into headlamps. In the future, some new types of light sources, such as lasers and OLEDs, should be tested due to their different luminescence characteristics compared with LEDs. Meanwhile, it is of extreme importance to optimize the primary optical design of LEDs to obtain collimated light or reduce the light-emitting angle as much as possible to improve the efficiency of this model.

To reduce the blue light hazard, this paper also proposed an integrated LED light source combined with a cyan LED to maintain the color performance and a white LED that is filtered by blue light. However, only adding a cyan LED is not enough; the ratio between the cyan LED and white LED was the key to this research. Therefore, we used optimization techniques based on a multi-spectral composite algorithm to calculate the coefficient of energy with different spectral bands or the LED of choice. The blue light hazard not only is present in display systems but also in every lighting system, especially in those with high color temperature light sources. However, this type of high color temperature light source, such as a white LED, is not only used as the light source of backlighting systems but also for our daily lighting needs. Therefore, the risk from blue light hazard cannot be ignored. Based on the standard of blue light hazard provided by the IEC, the hazard is in direct proportion to time.

Headlamp research is also linked to a high output and blue light hazard issues. The spectral attenuation model has been established to analyze the transmission of high beam lamp with different color temperatures. According to the trends of recent years, an increasing number of people are inclined to choose a high beam lamp with a high color temperature. However, based on the simulation results of our research, high color temperature high beam lamp is inferior to low color temperature high beam lamp in terms of not only the light transmission in low visibility weather conditions but also due to the blue light hazard to drivers (especially considering that the high output of headlamps increases this risk). According to the characteristics of color temperature, the ration of blue light in the spectrum grows as the color temperature increase. Therefore, in accordance with the results of research on the blue light hazard, drivers who tend to use headlamps with a high color temperature should wear blue-light-cutting glasses or change to low color temperature headlamps. On the other hand, if drivers who insist on using high color temperature headlamp while hoping to reduce the blue light hazard may choose the integrated LED headlamp combined with cyan LED blue light filtered white LED. And this is another future work which we want to develop further.

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Appendix

Monte Carlo ray tracing (Simulation):

In order to ensure the correct operation of Monte Carlo ray tracing, the definitions of illuminant surface source and material are the two minimum requirements.

As the setting of illuminant surface source, it mainly includes three important factors: Emission Type, rays and wavelength. Emission Type includes six options: None, Source property, Flux, Irradiance, Black body and Gray body. Normally, we choose Source property in this option bar. Meanwhile Source property also provide two optional patterns, existence light source from database of software and self-defined. Ray setting includes three factors: color of rays, number of rays and kinds of tracing ray (all rays, only random rays and only importance rays). All the setting of rays can be easily choose or input in the option bar. Wavelength setting need users input wavelength data one by one which do not allows files to be linked from outside.

As the setting of material, it mainly includes two important factors: Catalog of material and wavelength. Catalog also provide two optional patterns, existence light source from database of software and self-defined. As same as wavelength setting in illuminant surface source, it also need users input the wavelength data and allows to set only one data.

With the correct setting of illuminant surface source and material, Monte Carlo ray tracing can be perfected operated by software.

Modeling:

Distinguish from simulation by programming, all the optical simulation based on the model. Data setting also need to be attached with the surface or the body of model. In order to create the model, in addition to the material, shape and size of objects are also essential parameters.

Based on these reasons, technical parameters of models in the whole dissertation will be provided in the appendix, and it will be divided into two groups:

A. Model: Shape and size, Products and materials Optical parameters.

B. Simulation: Method, Purpose, Number of rays

Chapter 3

1. Fig 3. 18: Preliminary test result of a single SMD LED panel and lens array

Components and parts: Basement, LED, Lens

A:

Shape and size (L: length, W: width, T: thickness)

Basement	Sheet, $40 \times 40 \times 1$ mm (L $\times$ W $\times$ T)
LED	SMD, $5.6 \times 3.0 \times 1$ mm (L $\times$ W $\times$ T)
Lens	Shaped double hemisphere, $5.6 \times 3.0 \times 1$ mm (L $\times$ W $\times$ T) and 6.35mm (Diameter)

Products and materials

Basement	PLASTIC
LED	SAMSUNG 5630
Lens	PMMA

Optical parameters

	Lumino us flux	Refractiv e index	Radius of curvature	Focal length	Emitting angle	Waveleng th
Basement	×	×	×	×	×	×
LED	60lm	×	×	×	120°	546nm
Lens	×	1.49	3.18mm	4.8mm	×	×

B:

Method	Monte Carlo ray tracing Color of rays: Flux-based ray colors (red: 0.66~1, green:0.33~0.66, blue:0~0.33)
Purpose	The test of beam pattern reforming
Number of rays	1000

2. Fig 3. 19: Simulation result of single DIP LED panel and single lens on a lens array

Components and parts: Basement, LED, Lens

A:

Shape and size

Basement	Sheet, $20 \times 20 \times 3.7$ mm (L $\times$ W $\times$ H)
----------	---

LED	DIP, Length:8.3mm, Diameter:5mm
Lens	Disk shape, Thickness:2 mm, Diameter:10mm

Products and materials

Basement	PLASTIC
LED	NICHIA NSDW510GS-K1
Lens	Fresnel Lens, PMMA

Optical parameters

	Luminous flux	Refractive index	Ring width	Focal length	Emitting angle	Wavelength
Base	×	×	×	×	×	×
LED	30lm	×	×	×	35°	546nm
Lens	×	1.49	0.2mm	18.1mm	×	×

B:

Method	Monte Carlo ray tracing Color of rays: Flux-based ray colors (red: 0.66~1, green:0.33~0.66, blue:0~0.33)
Purpose	The test of beam pattern reforming
Number of rays	1000

3. Fig 3. 4: One unit of the DIP LED model and 3-layer units

Components and parts (right picture): Basement, LED, Lens 1(yellow), Lens 2 (orange), Lens 3 (blue)

A:

Shape and size

Basement	Sheet, 20×20×3.7 mm (L×W×H) Hole, Diameter: 4mm
LED	DIP, Length:8.3mm, Diameter:5mm
Lens 1	Fresnel Lens, Disk shape, Thickness:2 mm, Diameter:10mm
Lens 2	Reformed achromatic lens, Disk shape, Thickness 10mm, Diameter:28.28mm
Lens 3	Concave lens, Disk shape, Thickness 0.5mm, Diameter:5mm

Products and materials

Basement	PLASTIC
LED	NICHIA NSDW510GS-K1
Lens 1	Fresnel Lens, PMMA
Lens 2	Achromatic lens, lens A: BK7, lens B: SF12
Lens 3	Concave lens, PMMA

Optical parameters

	Luminous flux	Refractive index	Ring width	Focal length	Emitting angle	Wavelength	Radius of curvature
Basement	×	×	×	×	×	×	×
LED	30lm	×	×	×	35°	546nm	×
Lens 1	×	1.49	0.2mm	18.1mm	×	×	×
Lens 2	×	BK7:1.52 SF12:1.65	×	30mm	×	×	R1:24mm R2:76mm
Lens 3	×	1.49	×	-30mm	×	×	21mm

B:

Method	Monte Carlo ray tracing Color of rays: Flux-based ray colors (red: 0.66~1, green:0.33~0.66, blue:0~0.33)
Purpose	The smallest unit for simulation
Number of rays	1000

4. Fig 3. 5: DIP LED backlighting model with 3×14×10 units

Components and parts: 3 (layers)×14 (length)×10 (width) units of Fig. 3.4

A:

Shape and size

DIP LED backlighting model	Cuboid, 280×200×159 mm (L×W×T)
----------------------------	--------------------------------

Products and materials: same as Fig 3.4

Optical parameters: same as Fig 3.4

B:

Method	Demonstration
Purpose	The 14in standard multilayers backlighting model for demonstration
Number of rays	1000

5. Fig 3. 20: Four units of the DIP LED model and a 3-layers unit

Components and parts (right picture): 3 (layers) $\times$ 4 (length) $\times$ 4 (width) units of Fig. 3.4, Testing panel

A:

Shape and size

DIP LED backlighting model	Cuboid, 40 $\times$ 40 $\times$ 159 mm (L $\times$ W $\times$ T)
Testing panel	Sheet, 40 $\times$ 40 $\times$ 0.1mm (L $\times$ W $\times$ T)

Products and materials: same as Fig 3.4, Testing panel: plastic

Optical parameters: same as Fig 3.4, Testing panel: perfect absorber

B:

Method	Monte Carlo ray tracing Color of rays: Flux-based ray colors (red: 0.66~1, green:0.33~0.66, blue:0~0.33)
Purpose	The basic simulation model for facilitating the analysis of the illuminance distribution and color distribution
Number of rays	1000

6. Fig 3. 21: Trace performance of real rays

Components and parts: same as Fig 3.4

A: same as Fig 3.4

B:

Method	Monte Carlo ray tracing Color of rays: Energy distribution (red: 0.66~1, green:0.33~0.66, blue:0~0.33)
Purpose	Using smallest unit to test the pattern of beam through a group of lens
Number of rays	1000

7. Fig 3. 22: Trace performance of hypothetical perfectly collimated light rays

Components and parts: same as Fig 3.4

A: same as Fig 3.4

B:

Method	Monte Carlo ray tracing Color of rays: Flux-based ray colors (red: 0.66~1, green: 0.33~0.66, blue: 0~0.33)
Purpose	Using hypothetical perfectly collimated to test the pattern of beam through a group of lens
Number of rays	1000

8. Fig 3. 15: Comparison between the model of the three-layer DIP LED backlighting system and the single-layer SMD backlighting system

Components and parts (left picture): same as Fig 3.6

Components and parts (right picture): Basement, LED, Testing panel

A: right picture

Shape and size

Basement	Sheet, $40 \times 40 \times 1$ mm (L×W×T)
LED	SMD, $5.6 \times 3.0 \times 1$ mm (L×W×T)
Testing panel	Sheet, $40 \times 40 \times 0.1$ mm (L×W×T)

Products and materials

Basement	PLASTIC
LED	SAMSUNG 5630
Testing panel	Plastic

Optical parameters

	Luminous flux	Surface properties	Emitting angle	Wavelength
Basement	×	×	×	×
LED	60lm	×	120°	546nm
Testing panel	×	perfect absorber	×	×

B:

Method	Monte Carlo ray tracing 1. Color of rays: Flux-based ray colors (red: 0.66~1, green: 0.33~0.66, blue: 0~0.33) 2. Color of rays: wavelength-based ray colors Display rays from red to blue (long wavelength to short wavelength)
Purpose	For the comparison of the three-layer DIP LED backlighting system
Number of rays	1000

Chapter 4

1. Fig 4. 16: Simulation of ordinary LCD backlight LED by ray tracing

Components and parts: Basement, LED

A:

Shape and size

Basement	Sheet, 40×40×1 mm (L×W×T)
LED	SMD, 5.6×3.0×1 mm (L×W×T)

Products and materials

Basement	PLASTIC
LED	SAMSUNG 5630

Optical parameters

	Luminous flux	Emitting angle	Wavelength
Basement	×	×	×

LED	60lm	120°	380nm~780nm
-----	------	------	-------------

B:

Method	Monte Carlo ray tracing Color of rays: wavelength-based ray colors Display rays from red to blue (long wavelength to short wavelength)
Purpose	For testing the ordinary LCD backlighting system
Number of rays	1000

2. Fig 4. 6: The backlight model of AOC and BenQ

Components and parts (left picture): same as Fig 4.1

Components and parts (right picture): Basement, LED, Filter

A: right picture

Shape and size

Basement	Sheet, 40×40×1 mm (L×W×T)
LED	SMD, 5.6×3.0×1 mm (L×W×T)
Filter	Sheet, 40×40×1 mm (L×W×T)

Products and materials

Basement	PLASTIC
LED	SAMSUNG 5630
Filter	Blue light filter (filter wavelength under 455nm)

Optical parameters

	Luminous flux	Emitting angle	Wavelength
Baseme	×	×	×
LED	60lm	120°	380nm~780nm
Filter	×	×	Filter wavelength under 455nm

B:

Method	Monte Carlo ray tracing Color of rays: wavelength-based ray colors Display rays from red to blue (long wavelength to short wavelength)
Purpose	For the comparison of two blue light reduced backlighting model from AOC and BenQ
Number of rays	1000

3. Fig 4. 11: Backlight panel model of our method of filtering blue light

Components and parts (left picture): same as Fig 4.1

Components and parts (right picture): Basement, LEDs, Filter

A: right picture

Shape and size

Basement	Sheet, $40 \times 40 \times 1$ mm (L×W×T)
LED	SMD (blue color), $5.6 \times 3.0 \times 1$ mm (L×W×T) SMD (green color), $3.0 \times 3.0 \times 1$ mm (L×W×T)
Filter	Sheet, $40 \times 40 \times 1$ mm (L×W×T)

Products and materials

Basement	PLASTIC
LED	SAMSUNG 5630 Cyan LED
Filter	Blue light filter (filter wavelength under 455nm)

Optical parameters

	Luminous flux	Emitting angle	Wavelength
Basement	×	×	×
LED (SAMSUNG 5630)	60lm	120°	380nm~780nm
LED (Cyan)	5lm	120°	480nm
Filter	×	×	Filter wavelength under 455nm

B:

Method	Monte Carlo ray tracing Color of rays: wavelength-based ray colors Display rays from red to blue (long wavelength to short wavelength)
Purpose	For the comparison of two blue light reduced backlighting model from AOC and BenQ
Number of rays	1000

Chapter 5

1. Fig 5. 17: Simplified model of an integrated high-beam lamp

Components and parts: Reflector, LED

A:

Shape and size

Reflector	Parabolic, Thickness:0.5mm, Hole radius:10mm, Diameter:90mm
LED	Cylinder, Length:7mm, Diameters:7mm
Basement	Cylinder, Length:5mm, Diameters:20mm

Products and materials

Reflector	PMMA
LED	CREE XLamp
Basement	Plastic

Optical parameters

	Luminous flux	Emitting angle	Wavelength	Focal length	Reflectivity
Reflector	×	×	×	10mm	100%
LED	4022lm	360° (Self-setting)	546nm	×	×

Basement	×	×	×	×	0
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B:

Method	Monte Carlo ray tracing Color of rays: Flux-based ray colors (red: 0.66~1, green: 0.33~0.66, blue: 0~0.33)
Purpose	For the analysis of losses of emitted light energy
Number of rays	1000

2. Fig 5.3: Reflective sheet installed behind the lamp head of the high-beam lamp

Fig 5.2 as same as Fig 5.3

Components and parts: Reflector (blue), Halogen lamp (yellow), Reflective sheet (green)

A:

Shape and size

Reflector	Parabolic, Thickness:0.5mm, Hole radius:10mm, Diameter:90mm
LED	Cylinder, Length:7mm, Diameters:7mm
Reflective sheet	Sheet, Diameters:32mm, Thickness:0.1mm, Hole radius:3.5mm

Products and materials

Reflector	PMMA
LED	CREE XLamp
Reflective sheet	PMMA

Optical parameters

	Luminous flux	Emitting angle	Focal length	Wavelength	Reflectivity
Reflector	×	×	10mm	×	100%
LED	4022lm	360° (Self-setting)	×	380nm~780nm	0
Reflective sheet	×	×	∞	×	100%

B:

Method	Monte Carlo ray tracing Color of rays: Flux-based ray colors (red: 0.66~1, green: 0.33~0.66, blue: 0~0.33)
Purpose	For the improvement of losses of emitted light energy
Number of rays	1000

3. Fig 5. 5: High-beam lamp with reflective sheets with flat and curved surfaces

Components and parts (left picture): Reflector (blue), Halogen lamp (yellow), Flat reflective sheet (green)

Components and parts (right picture): Curved reflective sheet

A:

Shape and size

Reflector	Parabolic, Thickness:0.5mm, Hole radius:10mm, Diameter:90mm
LED	Cylinder, Length:7mm, Diameters:7mm
Flat reflective sheet	Sheet, Diameters:32mm, Thickness:0.1mm
Curved reflective sheet	Parabolic, Thickness:0.1mm, Hole radius:3.5mm, Diameters:44mm

Products and materials

Reflector	PMMA
LED	CREE XLamp
Flat reflective sheet	PMMA
Curved reflective sheet	PMMA

Optical parameters

	Luminous flux	Emitting angle	Focal length	Wavelength	Reflectivity
Reflector	×	×	10mm	×	100%
LED	4022lm	360° (Self-setting)	×	546nm	×
Flat reflective sheet	×	×	∞	×	100%
Curved reflective sheet	×	×	20mm	×	100%

B:

Method	Monte Carlo ray tracing Color of rays: Flux-based ray colors (red: 0.66~1, green: 0.33~0.66, blue: 0~0.33)
Purpose	For the analysis of different reflective sheet
Number of rays	1000

4. Fig 5. 9: Ray tracing from the high-beam lamp to the test panel

Same as Fig 5.3

5. Fig 5. 22: Model of a car with improved high-beam lamps and the test panel

Components and parts: Car, Testing panel

A:

Shape and size

Car	Cuboid, $4500 \times 2250 \times 1900\text{mm}$ (L $\times$ W $\times$ T)
Testing panel	Sheet, $20000 \times 20000 \times 1\text{mm}$ (L $\times$ W $\times$ T)

Products and materials

Car	Metal
Testing panel	Plastic

Optical parameters

	Luminous flux	Emitting angle	Wavelength	Reflectivity
Car	$4022\text{lm} \times 2$	$<5^\circ$	546nm	$\times$
Testing panel	$\times$	$\times$	$\times$	0%

B:

Method	Monte Carlo ray tracing Color of rays: Flux-based ray colors (red: 0.66~1, green: 0.33~0.66, blue: 0~0.33)
Purpose	For analyzing and improving the loss of emitted light energy from a car
Number of rays	1000

6. Fig 5.11: Ray tracing from the double high-beam lamps of a car to the test panel

Same as Fig 5.10

7. Fig 5. 23: Ray tracing from double high-beam lamps of car to a test panel at a distance of 100 m

Same as Fig 5.10

8. Fig 5. 13: Model of a car with improved high-beam lamps and appropriately sized test panel

Components and parts: Car, Testing panel, Road

A:

Shape and size

Car	Cuboid, $4500 \times 2250 \times 1900\text{mm}$ (L×W×T)
Testing panel	Sheet, $6000 \times 2000 \times 1\text{mm}$ (L×W×T)
Road	Sheet, $300000 \times 6000 \times 1\text{mm}$ (L×W×T)

Products and materials

Car	Metal
Testing panel	Plastic
Road	Cement

Optical parameters

	Luminous flux	Emitting angle	Wavelength	Reflectivity
Car	$4022\text{lm} \times 2$	$<5^\circ$	546nm	×
Testing panel	×	×	×	0%
Road	×	×	×	0%

B:

Method	Monte Carlo ray tracing Color of rays: Flux-based ray colors (red: 0.66~1, green: 0.33~0.66, blue: 0~0.33)
Purpose	For analyzing the illuminance at different distance from a car
Number of rays	1000~1000000

9. Fig 5. 16: Ray tracing from the car to the road at 100 m

Same as Fig 5.13

10. Fig 5. 24: Ray tracing from the car to the test panel

Components and parts: Car, Testing panel, Mist model

A:

Shape and size

Car	Cuboid, $4500 \times 2250 \times 1900\text{mm}$ (L $\times$ W $\times$ T)
Testing panel	Sheet, $20000 \times 20000 \times 1000\text{mm}$ (L $\times$ W $\times$ T)
Mist model	Cylinder, Diameter: 20000mm, Length:100000mm

Products and materials

Car	Metal
Testing panel	Plastic
Mist model	Mist(user-defined based on Fig 5.18)

Optical parameters

	Luminous flux	Emitting angle	Wavelength	Absorptivity
Car	$4022\text{lm} \times 2$	$<5^\circ$	380nm~780nm	$\times$
Testing panel	$\times$	$\times$	$\times$	100%
Mist model	$\times$	$\times$	$\times$	Based on the models of attenuation

B:

Method	Monte Carlo ray tracing Color of rays: wavelength-based ray colors Display rays from red to blue (long wavelength to short wavelength)
Purpose	For the analysis of transmission of high beams in the mist related to color temperature
Number of rays	1000~10000000

11. Fig 5. 25: Perspective drawing of rotatable high-beam lamp and ray-tracing results

Fig 5.23 as same as Fig 5.5

Components and parts: Reflector, LED (3000K), LED (6500K), lens (added in right picture)

A:

Shape and size

Reflector	Parabolic, Thickness:0.5mm, Hole radius:10mm, Diameter:90mm
LED(3000K)	Hemisphere, Diameters:7mm
LED(6500K)	Hemisphere, Diameters:7mm
Lens	Round, Thickness:10mm, Diameter:92mm

Products and materials

Reflector	PMMA
LED (3000K)	CREE XLamp
LED (6500K)	CREE XLamp
Lens	BK7

Optical parameters

	Luminous flux	Emitting angle	Wavelength	Focal length	Curvature radius	Reflectivity
Reflector	×	×	×	10mm	×	100%
LED (3000K and 6500K)	4022lm	120°	380nm ~780nm	×	×	×
Lens	×	×	×	286mm	300mm	0%

B:

Method	Monte Carlo ray tracing Color of rays: user-defined
Purpose	The proposal of rotatable double color-temperature high-beam lamp
Number of rays	1000

Chapter 6

1. Fig 6. 18: Model of an integrated high-beam lamp with 4 high output XHP70 LEDs

Components and parts: Reflector, LED×4, Basement 1(gray), Basement 2 (green)

A:

Shape and size

Reflector	Parabolic, Thickness:0.5mm, Hole radius:10mm, Diameter:90mm
LED	Hemisphere, Diameter:7mm
Basement 1	Cylinder, Length:4mm, Diameters:20mm
Basement 2	Cuboid, 7×7×9mm (L×W×T)

Products and materials

Reflector	PMMA
LED	CREE XLamp XHP70
Basement 1	Plastic
Basement 2	Plastic

Optical parameters

	Luminous flux	Emitting angle	Wavelength	Focal length	Reflectivity
Reflector	×	×	×	10mm	100%
LED	4022lm	120°	380nm~780nm	×	×
Basement 1	×	×	×	×	0
Basement 2	×	×	×	×	0

B:

Method	Monte Carlo ray tracing Color of rays: wavelength-based ray colors Display rays from red to blue (long wavelength to short wavelength)
Purpose	For the evaluation of output of high beam lamp by increasing the number of LED
Number of rays	1000000

2. Fig 6. 13: High beam lamp with multiple layers LED backlighting structure used in this case

Components and parts: Basement 1(gray), Basement 2 (orange), LED, Lens 1(pink), Lens 2 (purple), LED $\times$ 8

A:

Shape and size

Basement 1	Square Sheet, 20 $\times$ 20 $\times$ 3.7 mm (L $\times$ W $\times$ H) Hole, Diameter: 4mm
Basement 2	Disk shape, Thickness:1, Diameter:20mm Hole, Diameter: 4mm
LED	DIP, Length:8.3mm, Diameter:5mm
Lens 1	Achromatic lens, Disk shape, Thickness 10mm, Diameter:20mm
Lens 2	Concave lens, Disk shape, Thickness 0.5mm, Diameter:5mm
Whole model	Cuboid, 20 $\times$ 20 $\times$ 106mm (L $\times$ W $\times$ T)

Products and materials

Basement 1	Plastic
Basement 2	Plastic
LED	CREE XLamp XHP70
Lens 1	Achromatic lens, lens A: BK7, lens B: SF12
Lens 2	Concave lens, PMMA

Optical parameters

	Lumino us flux	Refractive index	Focal length	Emitting angle	Waveleng th	Radius of curvature
Basemen	×	×	×	×	×	×
LED	4022lm	×	×	120°	546nm	×
Lens 1	×	BK7:1.52 SF12:1.65	30mm	×	×	R1:24mm R2:76mm
Lens 2	×	1.49	-30mm	×	×	21mm

B:

Method	Monte Carlo ray tracing Color of rays: Flux-based ray colors (red: 0.66~1, green:0.33~0.66, blue:0~0.33)
Purpose	For the simulation of Ultra-high output high beam lamp with multiple-layer LED backlighting structure
Number of rays	100000

3. Fig 6. 14: High beam lamp with multiple layers LED backlighting structure and conventional high beam lamp

Same as Fig 6.1+ Fig 6.4

4. Fig 6. 15: 4 units of two layers of LED high beam lamp

Components and parts: Model of Fig 6.4×4 in transverse plane

A and B as same as Fig 6.4

5. Fig 6. 16: Ray tracing from the car installed 4 units of two layers of LED high beam lamp

Components and parts: Car, Lamps

A: car as same as car in Fig 5.10

Lamps as same as model in Fig 6.6

B:

Method	Monte Carlo ray tracing Color of rays: Flux-based ray colors (red: 0.66~1, green:0.33~0.66, blue:0~0.33)
Purpose	For the analysis of ultra-high output high beam lamp in cars
Number of rays	100000

6. Fig 6. 17: Ray tracing from the car to the test panel in the light attenuation model of fog using ultra-high output high beam lamp

Components and parts: Car, Testing panel, Fog model

A:

Shape and size

Car	Cuboid, $4500 \times 2250 \times 1900\text{mm}$ (L×W×T)
Testing panel	Sheet, $20000 \times 20000 \times 1000\text{mm}$ (L×W×T)
Mist model	Cylinder, Diameter: 20000mm, Length:100000mm

Products and materials

Car	Metal
Testing panel	Plastic
Fog model	Fog(user-defined based on Fig 5.22)

Optical parameters

	Luminous flux	Emitting angle	Wavelength	Absorptivity
Car	$4022\text{lm} \times 2$	$<5^\circ$	380nm~780nm	×
Testing panel	×	×	×	100%
Fog model	×	×	×	Based on the models of attenuation

B:

Method	Monte Carlo ray tracing Color of rays: wavelength-based ray colors Display rays from red to blue (long wavelength to short wavelength)
Purpose	For the analysis of transmission of ultra-high output high beams in the fog related to color temperature
Number of rays	100000



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