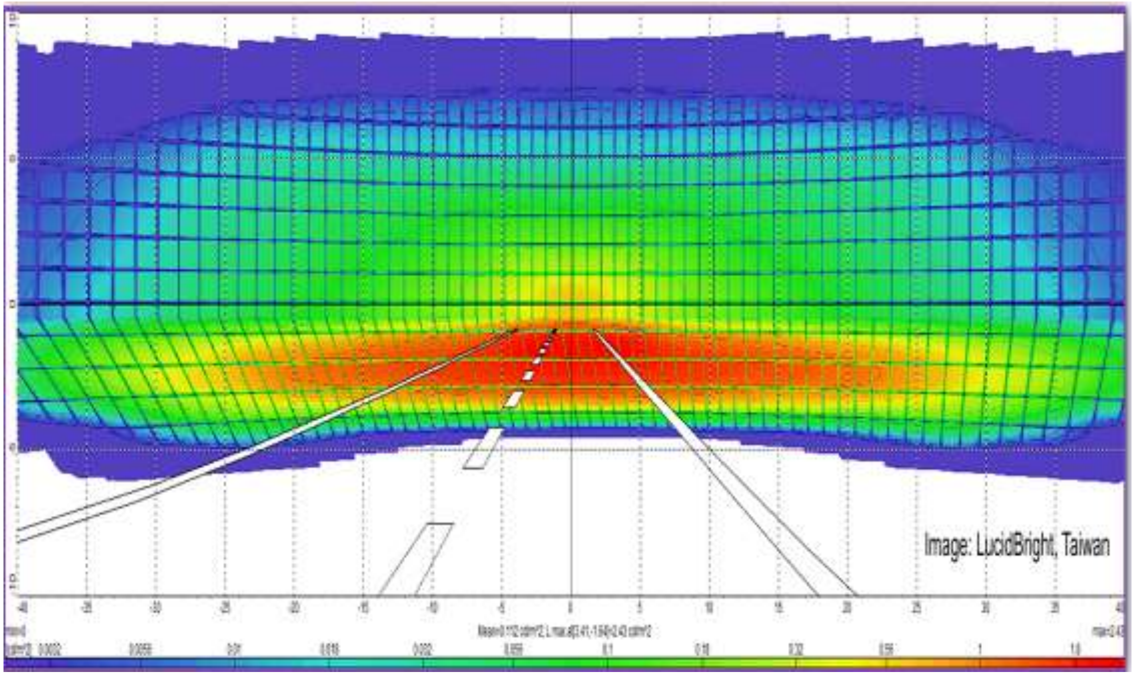


Image: NAL/Lucidshape

Customized Solution: A Cost Effective Design Approach to Adaptive Road Projection Headlamp

Adaptive, or pixel, headlamps represent a major leap in automotive lighting technology, delivering smarter and more efficient road illumination. By dynamically adjusting the light pattern to suit high- and low-beam conditions, these systems enhance visibility while minimizing glare for oncoming drivers—making nighttime driving both safer and more comfortable. Designing such advanced lighting, however, demands a deep understanding of imaging science. The process begins with precision lens design and extends into its inverse application, forming a projector system that ultimately shapes the light distribution on the road. In this work, I present the design of a cost-effective adaptive beam headlight—commonly known as a pixel light—that combines performance, efficiency, and practical feasibility.

Cost Effectiveness:
Traditional projection systems typically rely on stock lenses, which consist of multiple optical elements made from fixed material properties. These limitations restrict design flexibility and often increase manufacturing costs. In the automotive industry, even marginal cost increases are significant due to high-volume production, making cost efficiency critical. **These are the solution where 1 penny is too much!**

Custom lens solutions address this challenge by reducing the number of optical elements (for example, to as few as four) and utilizing cost-effective materials such as polycarbonate or PMMA. This approach lowers production costs while maintaining performance.

Our design prioritizes high illumination, accurate color correction, and minimal distortion and field curvature. A key factor in selecting or designing lenses is telecentricity. A more telecentric lens system better preserves etendue, resulting in greater light intensity and efficiency in the projected output.

Cost saving and performance enhancement approach in the headlamp design parameters are written in Green.

REQUIREMENTS AND SUCCESS CRITERIA:

We begin with the requirements outlined in the LucidShape pixel lighting example and define the success criteria for this design accordingly. Notably, the LED or display size is specified by a rectangular pupil measuring 4 mm × 8 mm in the vertical and horizontal dimensions. The projected light image on the roadway is expected to achieve a field of view (FOV) of 8° × 16° (vertical and horizontal). In a nutshell this is the main goal. Regardless of how the lens stack is designed, the key objective is to demonstrate that a 4 mm × 8 mm image can be projected uniformly 25 meters down the road with an 8° × 16° beam or 7 meter x 3.5 meter projection. If this condition is met, the design can be considered successful, as this ultimately defines the performance requirement.

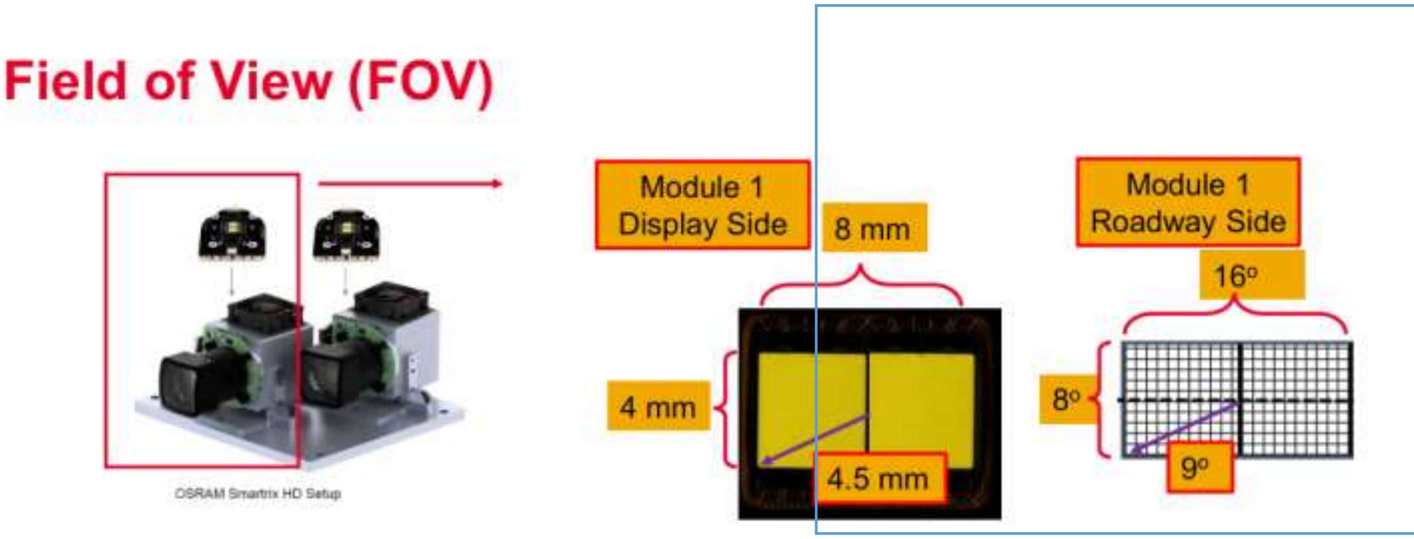


Figure 1: Requirement derived from lucidshape example of pixel lighting.

We start with the typical requirements of pixel light:

- Each headlamp will cover 16 degree FOV
- To cover the entire 32° x 8° (requires two headlamps).
- At projection distance is 25 meter and the horizontal and vertical FOV is 16 x 8 degrees, which based on trigonometric projection make a horizontal and vertical projection area 7 m x 3.5 meter approximately (each headlamp illuminating the projection plane).
- Illuminance: 110 lx / 25 m (32 lx required)
- Image Projection distance: Infinite Conjugate (However testing will be performed at 25m)
- Image size: spatial width of 4.5 mm for the pixel array in the image plane
- Since in the image size is 4.5 mm and the diagonal half-FOV in the projection plane is 9°
- Effective focal length of the projection system is: 4.5/tan(9°) = about 28 mm
- Lens Materials: plastic
- Number of lens element: 4
- Etendue: preserved via telecentricity for High Lux value on the screen projected 25 meter on roadway.
- F/#: Smaller the better light output
- Track length and back focal distance

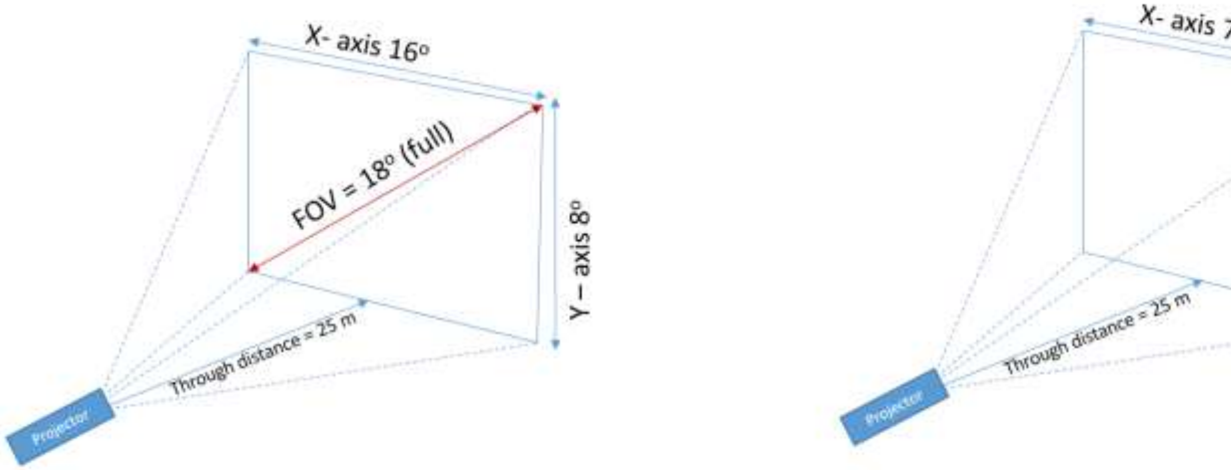
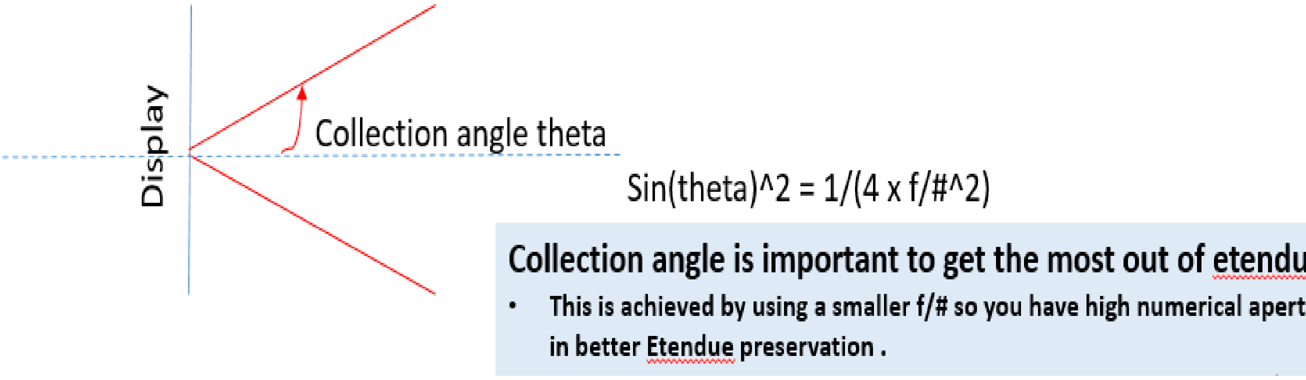


Figure 2: Projection Screen of headlamp at 25 meter (success criteria)

To improve the initial design's effectiveness, we will slightly increase the field of view (FOV) so that image quality remains robust when projected onto a smaller FOV. In other words, if the lens system performs well at a larger FOV, it is reasonable to assume it will perform at least as well at a slightly smaller FOV. This adjustment will slightly enlarge the image plane relative to the emission area, which is actually beneficial for overall coverage while also reducing vignetting.

The five bullet points highlighted above directly impact both the performance and cost of the headlamp design. Based on this assumption, a four-element plastic lens stack has been designed with a low F/# while maintaining appropriate telecentric conditions. The required image size is known to be approximately 4 mm × 8 mm, or slightly larger, corresponding to the emission area of the pixel light source. Using first-order optical principles and a 16° field of view, we calculate a rectangular pupil size (effective pupil diameter, EPD) of approximately 12 mm.



Collection angle is important to get the most out of etendu

- This is achieved by using a smaller f/# so you have high numerical apert in better Etendue preservation .

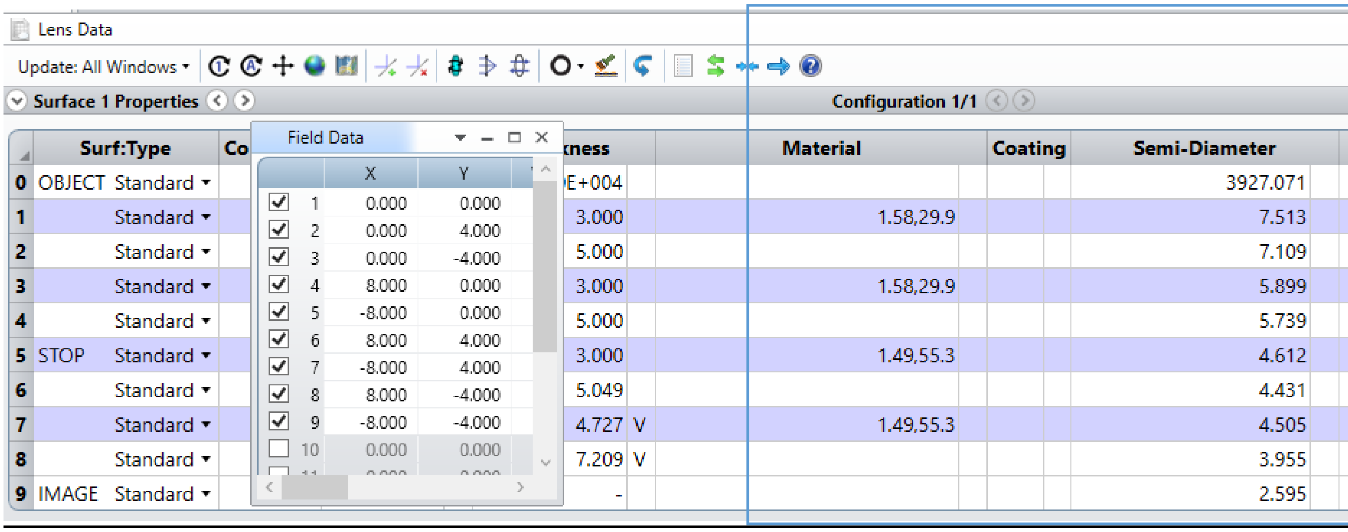
Figure 3: one can conclude that, smaller the F/# greater the collection angle and hence greater the light throughput or Etendue.

At the start, the headlamp can be designed with an initial, relaxed configuration using a focal ratio of f/# = focal length / EPD = 28 / 12 = 2.33. A relatively large f/# is preferred at this stage because it helps limit optical aberrations in the system. Subsequently, both the entrance pupil diameter (EPD) and the f/# can be adjusted and optimized to maintain good optical performance while gradually reducing the f/#. Throughout this process, the image size is kept *constant at 4 mm × 8 mm but slightly larger, while ensuring that the collection angle remains sufficiently large to achieve high optical throughput.*

Lens Materials: *Only two types of lens materials were considered in our configuration: PMMA and polycarbonate (POLY). Plastic lenses were selected exclusively, and cemented lens structures were not allowed due to cost-saving constraints. The center thickness was limited to a maximum of 10 mm to avoid unnecessary bulk, while the edge thickness was maintained above 0.6 mm to ensure manufacturability.*

Based on these constraints, several design configurations were generated using optical design software to satisfy the requirements defined in Figure 1. In operation, when the projector is built, a 4 mm × 8 mm LED emission area is illuminated through the lens stack. The system is designed such that the light is properly redistributed to produce a uniform image at a 25-meter projection distance, achieving a minimum illumination of at least 32 lux over a 7 m × 3.5 m display area in both horizontal and vertical directions.

Design:



	Surf:Type		Co	...kness		Material	Coating	Semi-Diameter
0	OBJECT	Standard		E+004				3927.071
1		Standard		3.000		1.58,29.9		7.513
2		Standard		5.000				7.109
3		Standard		3.000		1.58,29.9		5.899
4		Standard		5.000				5.739
5	STOP	Standard		3.000		1.49,55.3		4.612
6		Standard		5.049				4.431
7		Standard		4.727	V	1.49,55.3		4.505
8		Standard		7.209	V			3.955
9	IMAGE	Standard		-				2.595

		X	Y
☑	1	0.000	0.000
☑	2	0.000	4.000
☑	3	0.000	-4.000
☑	4	8.000	0.000
☑	5	-8.000	0.000
☑	6	8.000	4.000
☑	7	-8.000	4.000
☑	8	8.000	-4.000
☑	9	-8.000	-4.000
☐	10	0.000	0.000

Figure 4: From lens data editor it can be seen the FOV of 8x16 degree and 4 plastic lenses were used to meet the requirement.

What can be observed from figure 4 is that the field angle (FOV) is set to 8° × 16° in the vertical and horizontal directions. Four lenses were used, and the model glasses shown are all made of plastic, primarily acrylic and polycarbonate. Although the design is based on an infinite conjugate optical system, a 25 m projection is modeled by the first rays striking the system.

Results:

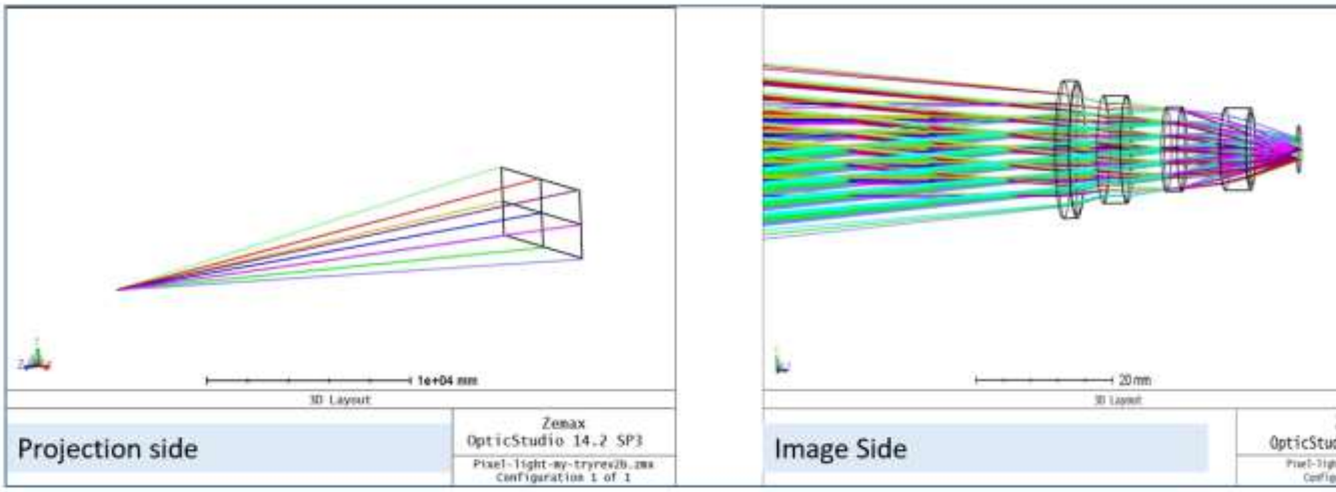


Figure 5: Lens design stack both on the image side and the projection side

Field Curvature and distortion:

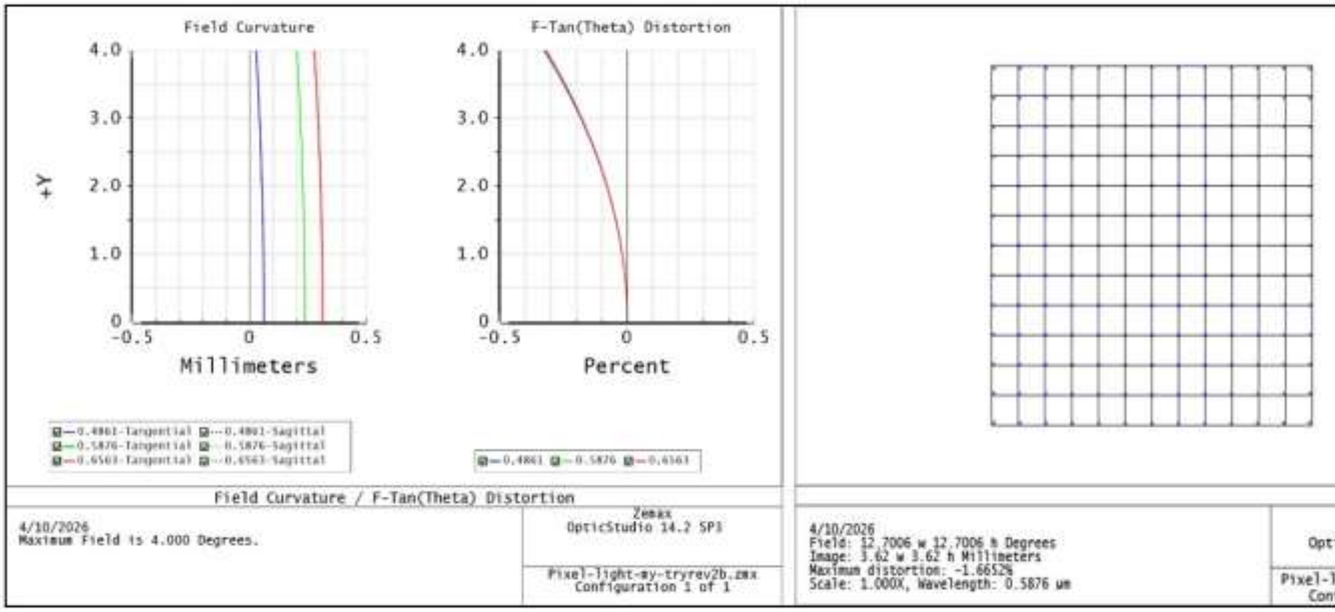
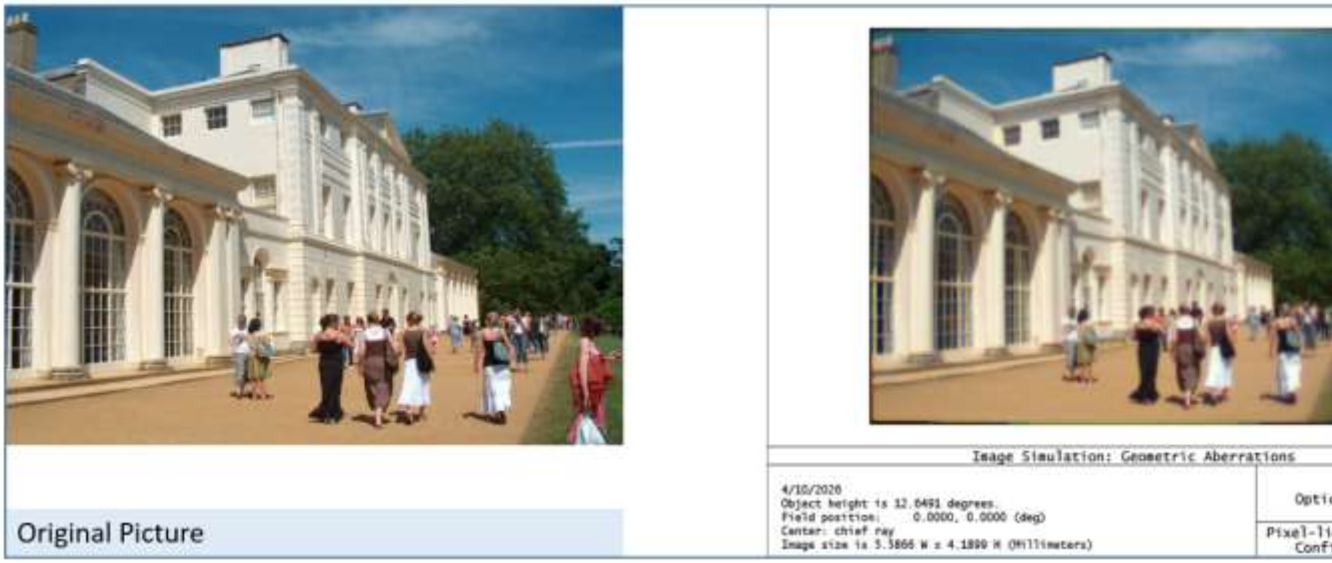


Figure 6: Performance of the lens after distortion and field curvature correction

Image Simulation

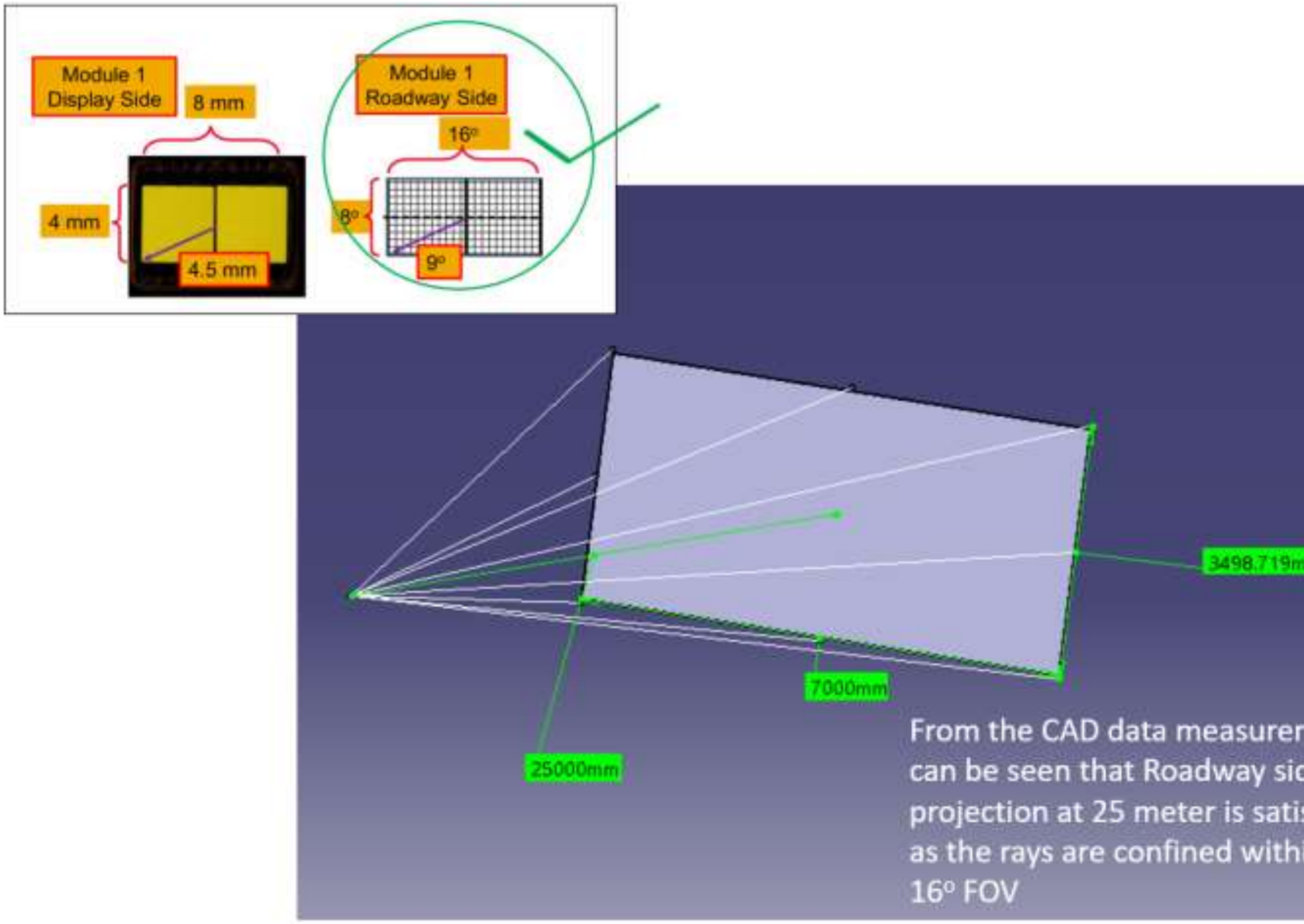


```
4/10/2026
Object height is 12.6491 degrees.
Field position:     0.0000, 0.0000 (deg)
Center: chief ray
Image size is 5.3866 W x 4.1899 H (Millimeters)
```

Figure 7: Image Simulation

A few comments on the figure above: In these types of systems, the primary focus is on telecentricity rather than image quality. In this design, a simple plastic lens with radial curvature was used. Incorporating aspheric lenses could further improve image quality.However, the main purpose of the design is to achieve a low F/# while maintaining good telecentric conditions, in order to maximize light throughput (see Figure 3).

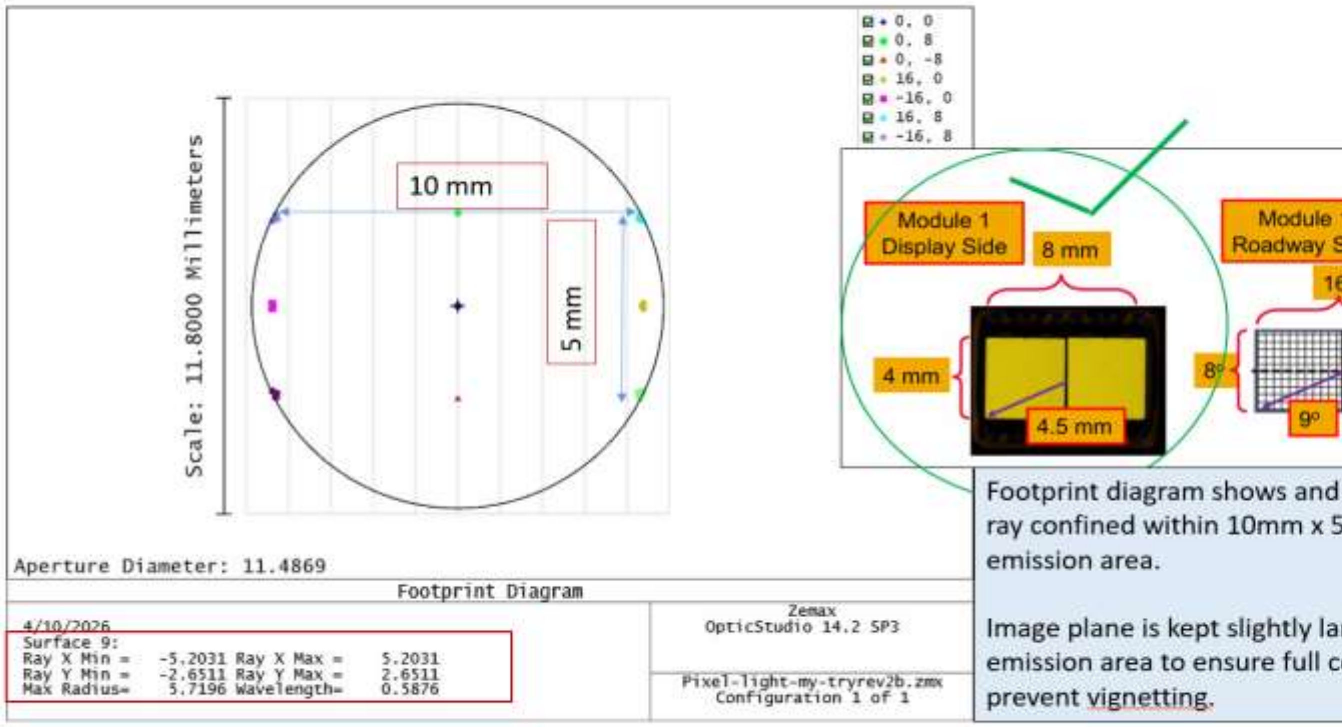
Finally: CAD Export to verify the projection image plane.



From the CAD data measuren
can be seen that Roadway sic
projection at 25 meter is satis
as the rays are confined withi
16° FOV

Figure 8: CAD projection data with measurement

Image plane



```
Aperture Diameter: 11.4869
```

```
4/10/2026
Surface 9:
Ray X Min =   -5.2031 Ray X Max =    5.2031
Ray Y Min =   -2.6511 Ray Y Max =    2.6511
Max Radius=    5.7196 Wavelength=    0.5876
```

Footprint diagram shows and
ray confined within 10mm x 5
emission area.

Image plane is kept slightly la
emission area to ensure full c
prevent vignetting.

Figure 9: footprint diagram to demonstrate the size of the image confined within the LED emission area.

Conclusion:

This work demonstrates that high-performance adaptive headlamp systems do not require overly complex or expensive optics. With the right design strategy, it is possible to deliver scalable, cost-effective solutions for next-generation automotive lighting.

More detailed illumination analysis (Part II) coming soon.

ILLUMINATION: The system if **reversed** will create a projection on the screen such that it can image lights uniformly on a screen at 25 meter with 7meter x 3.5 meter spread in horizontal and vertical direction….