SYNOPSYS®
Silicon to Software™

Case Study:
Designing an Automotive Backup Camera

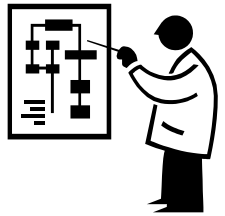
Presented by David Hasenauer

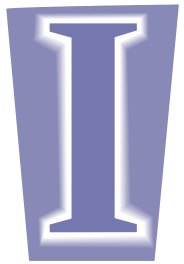
December 2017

Goal: Design a Compact, Wide-Angle, Manufacturable Automotive Back-Up Camera

- For this case study, we will:
  - –Monitor performance against System Specifications and Goals
  - –Find a suitable starting system
  - –Optimize to control manufacturability
  - –Determine the best asphere locations
  - –Simulate the camera view
  - –Plus much more!

Design Process



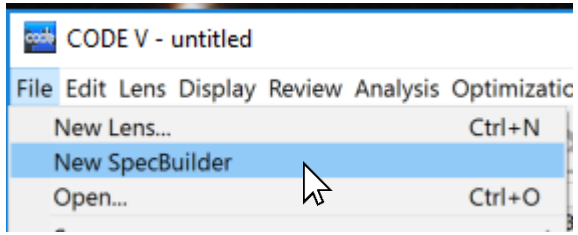


Identify the Project Specifications and Goals

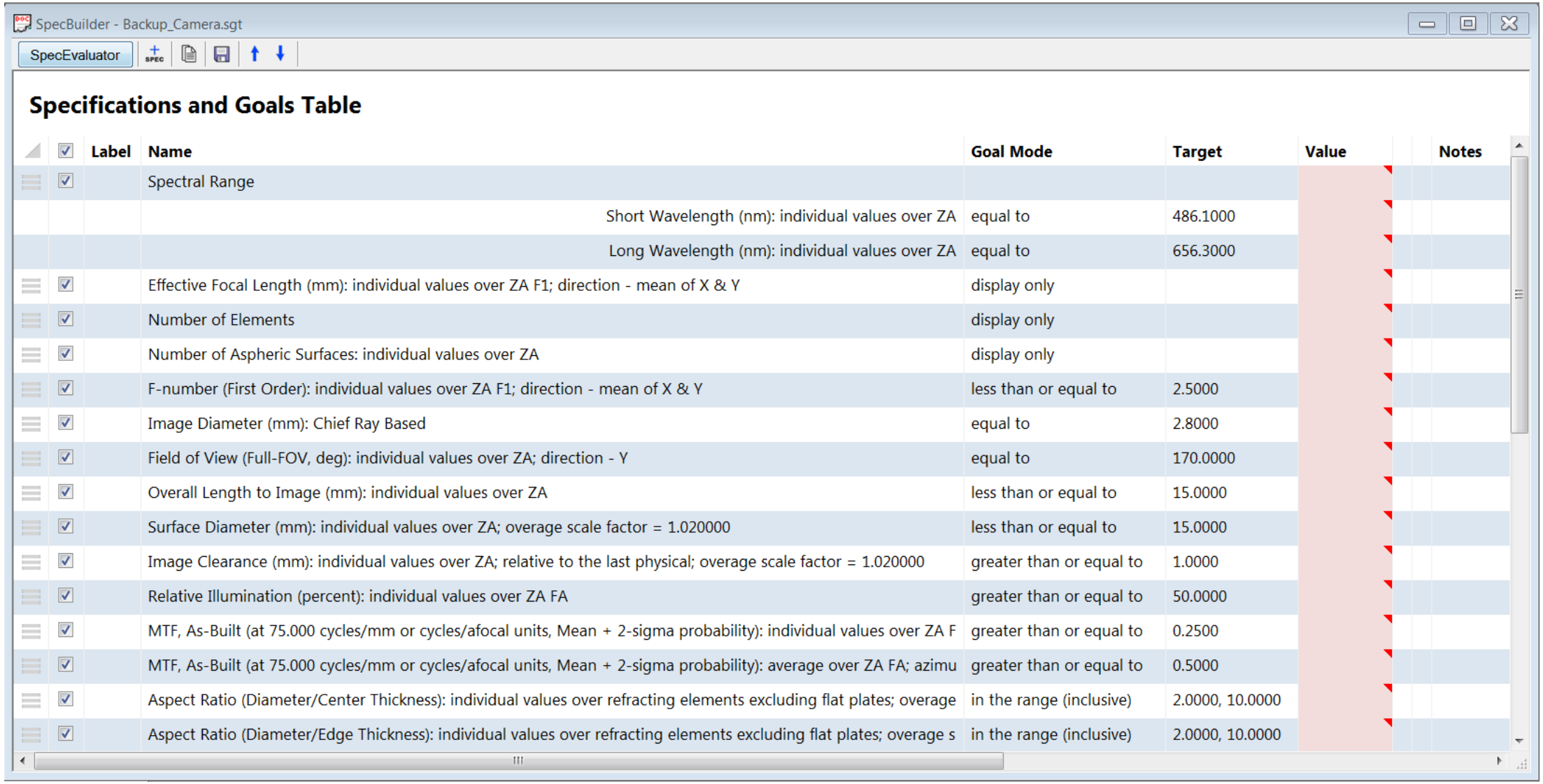
System Specifications & Goals:

Parameter	Specification
Wavelengths	486.1– 656.3 nm
Focal length; # of Elements; # of Aspheres	Monitor
F-number	f/2.5
Sensor Full-diagonal	2.8 mm
Field Full-diagonal	170°
Overall Length	< 15 mm
Lens Diameters	< 15 mm
Lens to Sensor clearance	> 1.0 mm
Relative Illumination	> 50%
As-Built MTF @75 c/mm (0° & 90° Azimuth), Mean+2σ Probability • Minimum over field • Average over field	 > 0.25 > 0.50
Diameter/CT (1/ATC)	>2:1;<10:1 (goal)
Diameter/ET (1/ATE)	>2:1;<10:1 (goal)

Let's "communicate" this to the Software



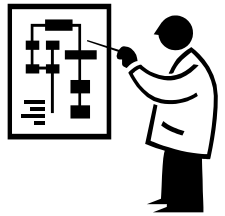
Create a Specifications & Goals Table:



Specifications and Goals Table

Label	Name	Goal Mode	Target	Value	Notes
	Spectral Range				
	Short Wavelength (nm): individual values over ZA	equal to	486.1000		
	Long Wavelength (nm): individual values over ZA	equal to	656.3000		
	Effective Focal Length (mm): individual values over ZA F1; direction - mean of X & Y	display only			
	Number of Elements	display only			
	Number of Aspheric Surfaces: individual values over ZA	display only			
	F-number (First Order): individual values over ZA F1; direction - mean of X & Y	less than or equal to	2.5000		
	Image Diameter (mm): Chief Ray Based	equal to	2.8000		
	Field of View (Full-FOV, deg): individual values over ZA; direction - Y	equal to	170.0000		
	Overall Length to Image (mm): individual values over ZA	less than or equal to	15.0000		
	Surface Diameter (mm): individual values over ZA; overage scale factor = 1.020000	less than or equal to	15.0000		
	Image Clearance (mm): individual values over ZA; relative to the last physical; overage scale factor = 1.020000	greater than or equal to	1.0000		
	Relative Illumination (percent): individual values over ZA FA	greater than or equal to	50.0000		
	MTF, As-Built (at 75.000 cycles/mm or cycles/afocal units, Mean + 2-sigma probability): individual values over ZA F	greater than or equal to	0.2500		
	MTF, As-Built (at 75.000 cycles/mm or cycles/afocal units, Mean + 2-sigma probability): average over ZA FA; azimu	greater than or equal to	0.5000		
	Aspect Ratio (Diameter/Center Thickness): individual values over refracting elements excluding flat plates; overage	in the range (inclusive)	2.0000, 10.0000		
	Aspect Ratio (Diameter/Edge Thickness): individual values over refracting elements excluding flat plates; overage s	in the range (inclusive)	2.0000, 10.0000		

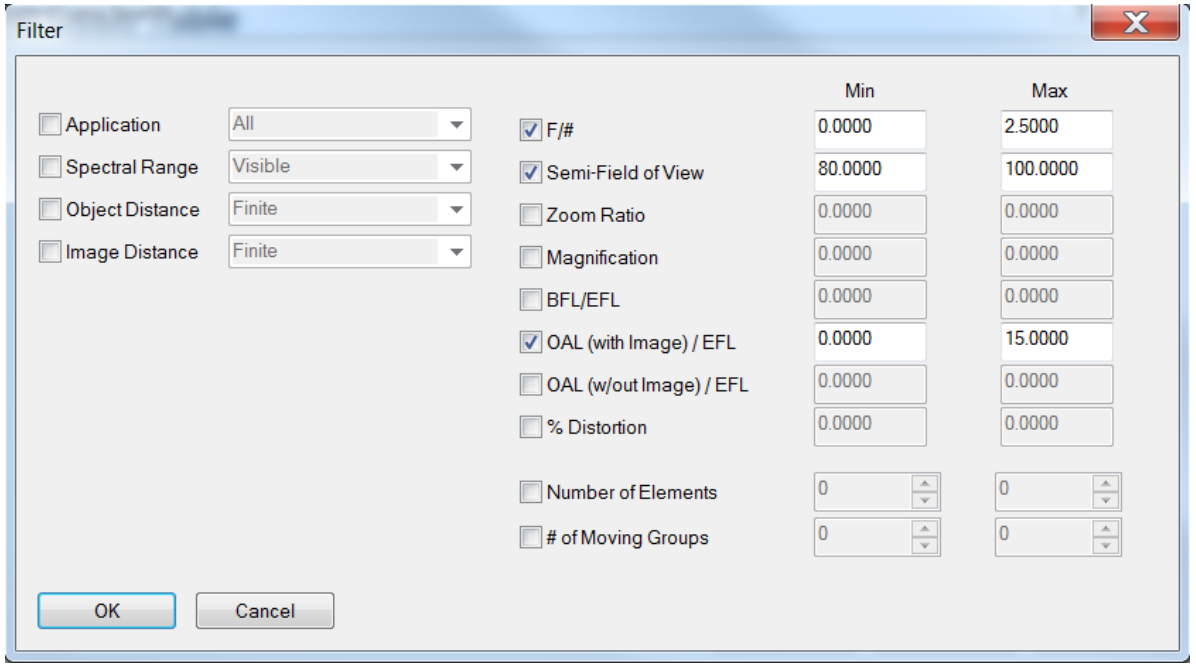
Design Process



Find an Appropriate Starting System

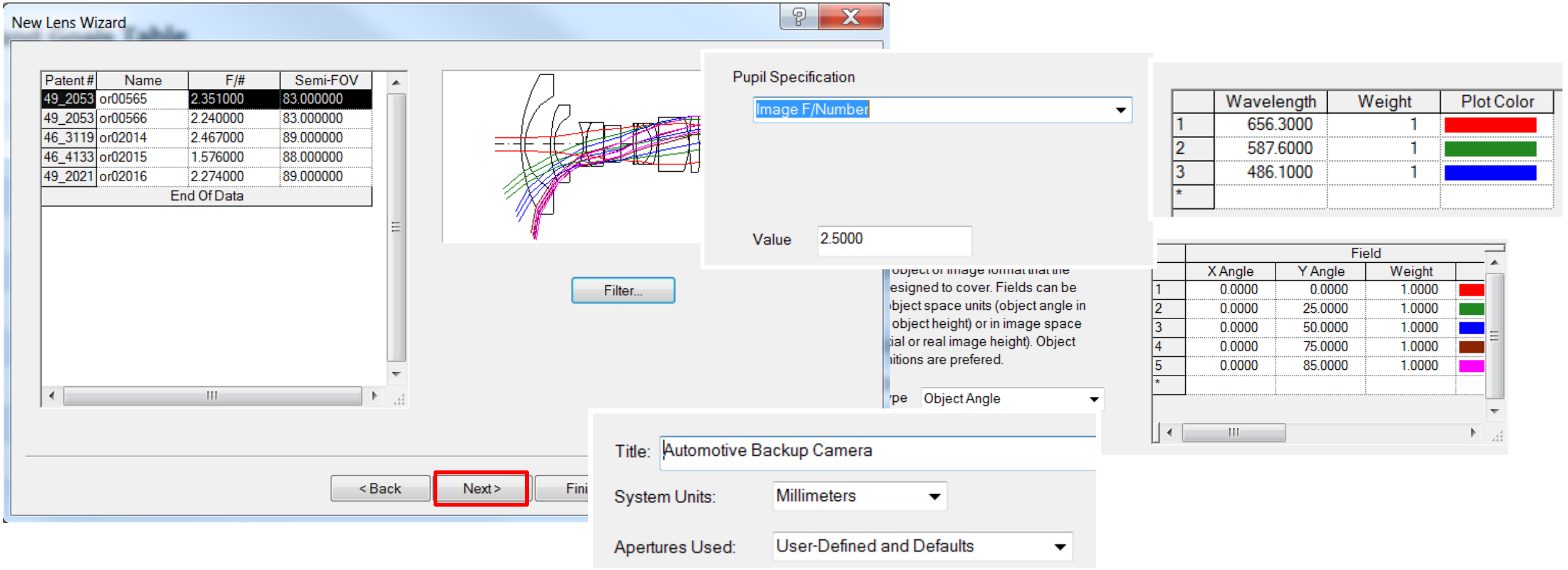
Patent Lens Search

- Search patent database of 2500 patent lenses for a suitable starting point:
  - –f/# < f/2.5
  - –Semi-FOV > 80° < 100°
  - –OAL/EFL (including Image) < 15

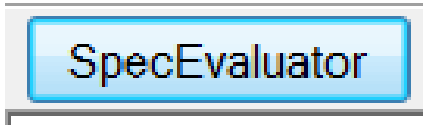


Five Candidates were Identified:

- The pupil, wavelengths, and fields were adjusted for the selected lens:



Evaluate Starting System against Specs:



SpecBuilder - Backup_Camera.sgt

SpecEvaluator

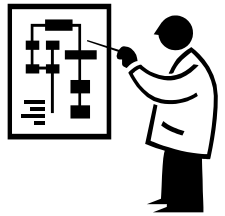
Specifications and Goals Table

Label	Name	Goal Mode	Target	Value	Notes
	Effective Focal Length (mm): individual values over ZA F1; direction - mean of X & Y	display only		1.07849	
	Number of Elements	display only		10.00000	
	Number of Aspheric Surfaces: individual values over ZA	display only		0	
	F-number (First Order): individual values over ZA F1; direction - mean of X & Y	less than or equal to	2.50000	2.50000	
	Image Diameter (mm): Chief Ray Based	equal to	2.80000	2.80000	
	Field of View (Full-FOV, deg): individual values over ZA; direction - Y	equal to	170.00000	170.00000	
	Overall Length to Image (mm): individual values over ZA	less than or equal to	15.00000	9.19081	
	Surface Diameter (mm): individual values over ZA; overage scale factor = 1.020000	less than or equal to	15.00000	[1.16237, 5.07758]	
	Image Clearance (mm): individual values over ZA; relative to the last physical; overage	greater than or equal to	1.00000	2.95191	
	Relative Illumination (percent): individual values over ZA FA	greater than or equal to	50.00000	[42.60805, 100.00000	
	MTF (at 150.000 cycles/mm or cycles/afocal units): individual values over ZA FA DA; azi	display only		[0.03995, 0.13881]	
	MTF (at 150.000 cycles/mm or cycles/afocal units): average over ZA FA DA; azimuth - m	display only		0.08929	
	MTF, As-Built (at 75.000 cycles/mm or cycles/afocal units, Mean + 2-sigma probability)	greater than or equal to	0.25000		
	MTF, As-Built (at 75.000 cycles/mm or cycles/afocal units, Mean + 2-sigma probability)	greater than or equal to	0.50000		
	Aspect Ratio (Diameter/Center Thickness): individual values over refracting elements e	in the range (inclusive)	2.00000, 10.00000	[1.88878, 39.76608]	
	Aspect Ratio (Diameter/Edge Thickness): individual values over refracting elements exc	in the range (inclusive)	2.00000, 10.00000	[2.26089, 10.27066]	

The system level and mechanical specifications are generally being held, except for the Element Aspect Ratios.

The nominal system performance is quite poor, and no tolerances are defined so we cannot evaluate the as-built MTF

Design Process

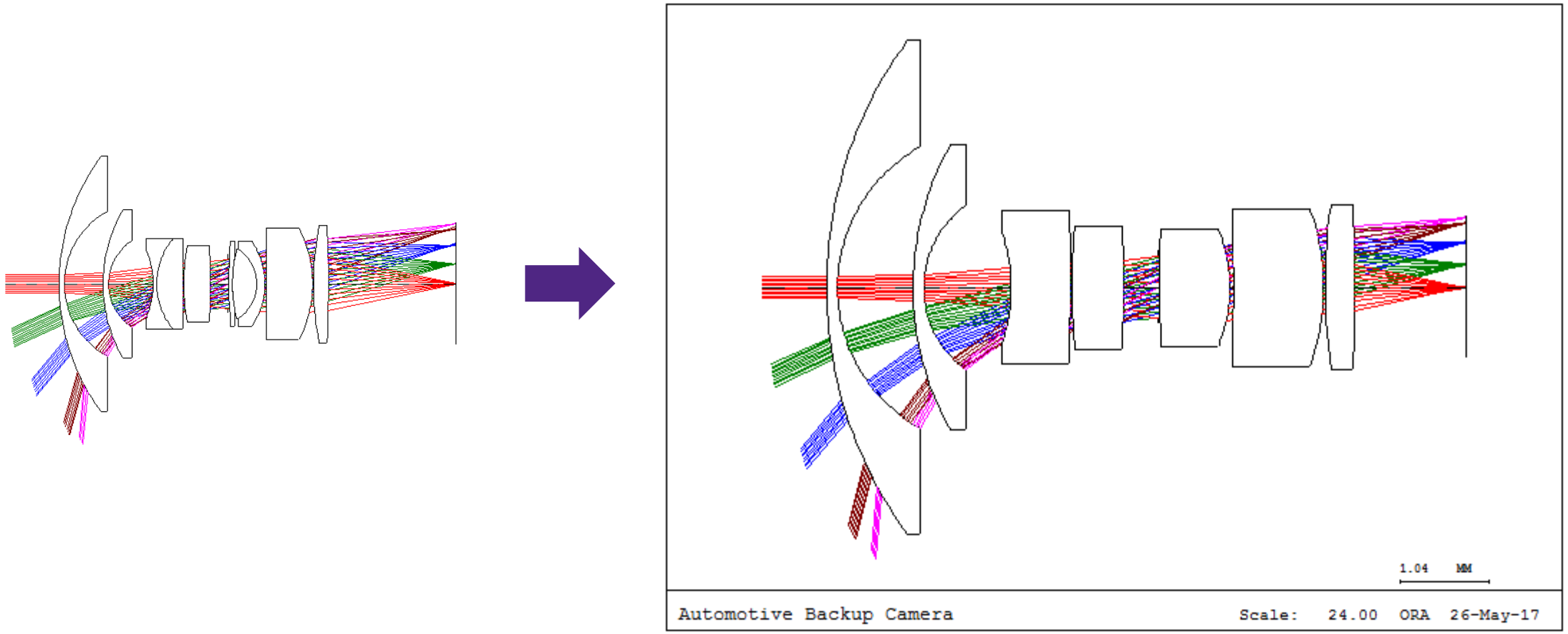


Remove Cemented Components

Determine Optimization Variables and Constraints

Cemented Components Are Impractical for a Small Lens, in Which Many of the Elements May Be Molded

- Remove the cemented components:



Make Radii, Thicknesses & Glass Variable

Lens Data Manager

System Data... | Surface Properties...

Surface #	Surface Name	Surface Type	Y Radius	Thickness	Glass	Refract Mode	Y Semi-Aperture
Object		Sphere	Infinity	Infinity		Refract	
1		Sphere	4.9588 V	0.1277 V	620410.603000 V	Refract	2.4517
2		Sphere	1.9108 V	0.8937 V		Refract	1.6646
3		Sphere	3.4268 V	0.1277 V	620410.603000 V	Refract	1.3344
4		Sphere	1.1985 V	1.0298 V		Refract	0.9768
5		Sphere	-2.0587 V	0.6979 V	620410.603000 V	Refract	0.6640
6		Sphere	-42.5557 V	0.0171 V		Refract	0.5248
7		Sphere	5.7746 V	0.6127 V	830560.365000 V	Refract	0.5120
8		Sphere	-20.4468 V	0.4043 V		Refract	0.4107
Stop		Sphere	Infinity	0.0213 V		Refract	0.3609
10		Sphere	11.2336 V	0.8342 V	755200.275000 V	Refract	0.3651
11		Sphere	-1.8172 V	0.0425 V		Refract	0.4878
12		Sphere	-34.9692 V	1.0639 V	620410.603000 V	Refract	0.5050
13		Sphere	-2.8325 V	0.0171 V		Refract	0.6803
14		Sphere	6.8050 V	0.3490 V	620410.603000 V	Refract	0.7028
15		Sphere	-29.7475 V	1.3896 S		Refract	0.7212
Image		Sphere	Infinity	-0.0729 V		Refract	0.8390

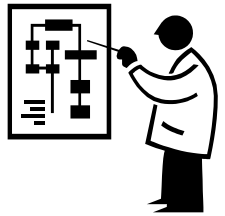
End Of Data

Optimization Constraints

- Initial Constraints*:
  - Image scale, overall length, image clearance, front lens semi-diameter, element aspect ratios (CT/Diameter & ET/Diameter), full-field relative illumination
- Final Constraints:
  - All of the initial constraints, plus:
    - Constraints to prevent the back surfaces of the front two elements from optimizing to hemispheres
    - General tolerance sensitivity constraints (**SN2**)
      - This made a huge difference in the eventual as-built performance
    - Explicit center thickness constraints for the last two elements
      - Their aspect ratios met spec, but due to their small size, we wanted them to be thicker

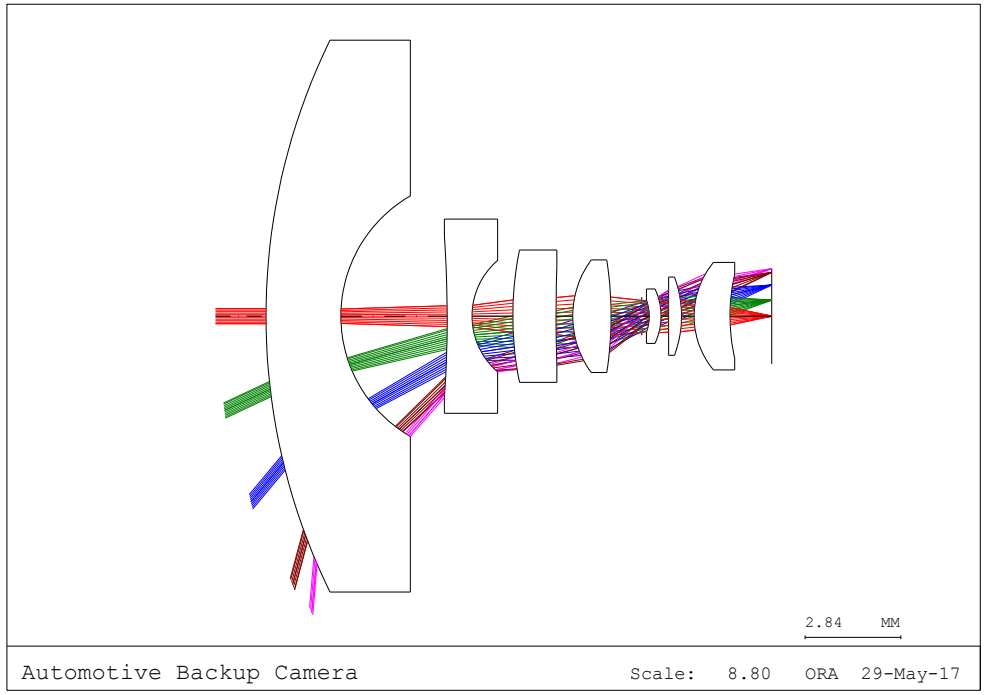
* The full set of optimization constraints is rarely known at the start of the design. The designer must monitor the evolution of the design, and potentially add new constraints, or relax some previously entered constraints to guide the lens design.

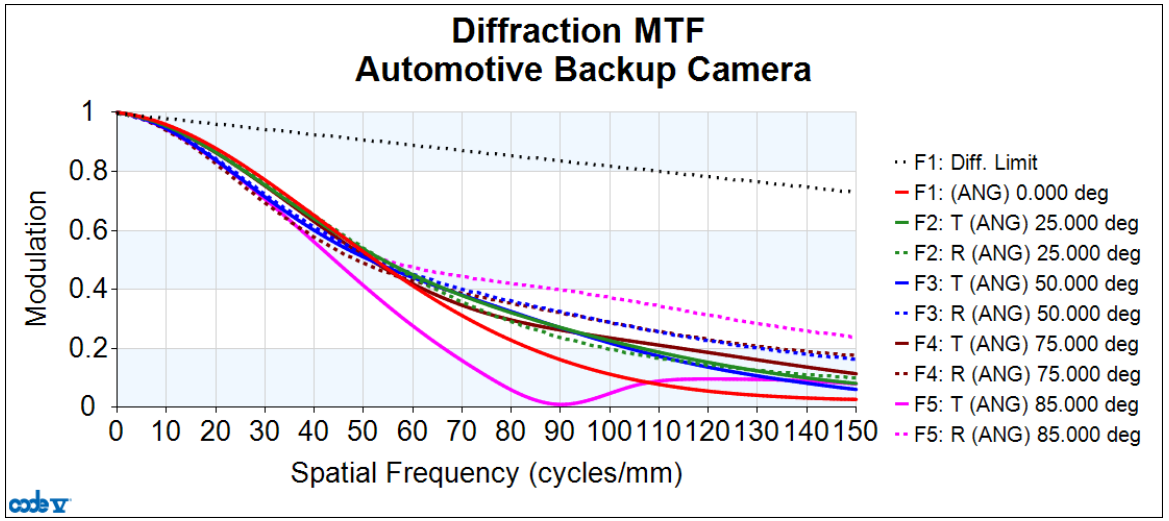
Design Process

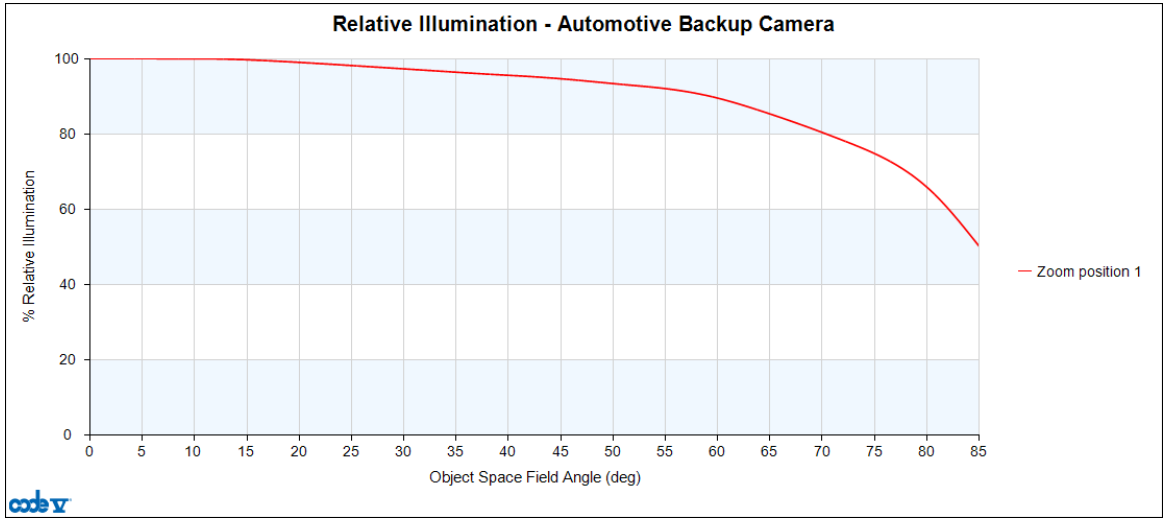


Evaluate Starting Performance

All-Spherical Optimized System Nominal Performance







Evaluate All Spherical System against Specs:

SpecBuilder - Backup_Camera.sgt

SpecEvaluator

Specifications and Goals Table

Label	Name	Goal Mode	Target	Value	Notes
	Field of View (Full-FOV, deg): individual values over ZA; direction - Y	equal to	170.0000	170.0000	
	Overall Length to Image (mm): individual values over ZA	less than or equal to	15.0000	15.0000	
	Surface Diameter (mm): individual values over ZA; overage scale factor =	less than or equal to	15.0000	[0.9545, 14.9094]	
	Image Clearance (mm): individual values over ZA; relative to the last phy	greater than or equal to	1.0000	1.0943	
	Relative Illumination (percent): individual values over ZA FA	greater than or equal to	50.0000	[50.2763, 100.0000]	
	MTF (at 150.000 cycles/mm or cycles/afocal units): individual values over	display only		[0.0293, 0.1629]	
	MTF (at 150.000 cycles/mm or cycles/afocal units): average over ZA FA D	display only		0.1079	
	MTF, As-Built (at 75.000 cycles/mm or cycles/afocal units, Mean + 2-sig	greater than or equal to	0.2500	[0.0000, 0.3170]	
	MTF, As-Built (at 75.000 cycles/mm or cycles/afocal units, Mean + 2-sig	greater than or equal to	0.5000	0.2279	
	Aspect Ratio (Diameter/Center Thickness): individual values over refracti	in the range (inclusive)	2.0000, 10.0000	[2.3518, 6.7144]	
	Aspect Ratio (Diameter/Edge Thickness): individual values over refracting	in the range (inclusive)	2.0000, 10.0000	[2.7368, 6.7956]	
	CODE V Model Attribute - System Units	equal to	Millimeters	Millimeters	
	CODE V Model Attribute - Field				
	Number of Fields	equal to	5	5	

The system level and mechanical specifications are being held, including the Element Aspect Ratios.

The as-built system performance is far below spec.

Image Simulation

- The parking lot scene was created using an iPhone in panoramic mode which approximately maps equal angles in the scene to equal distances on the image
  - Object Angle mapping is supported in Image Simulation

Object

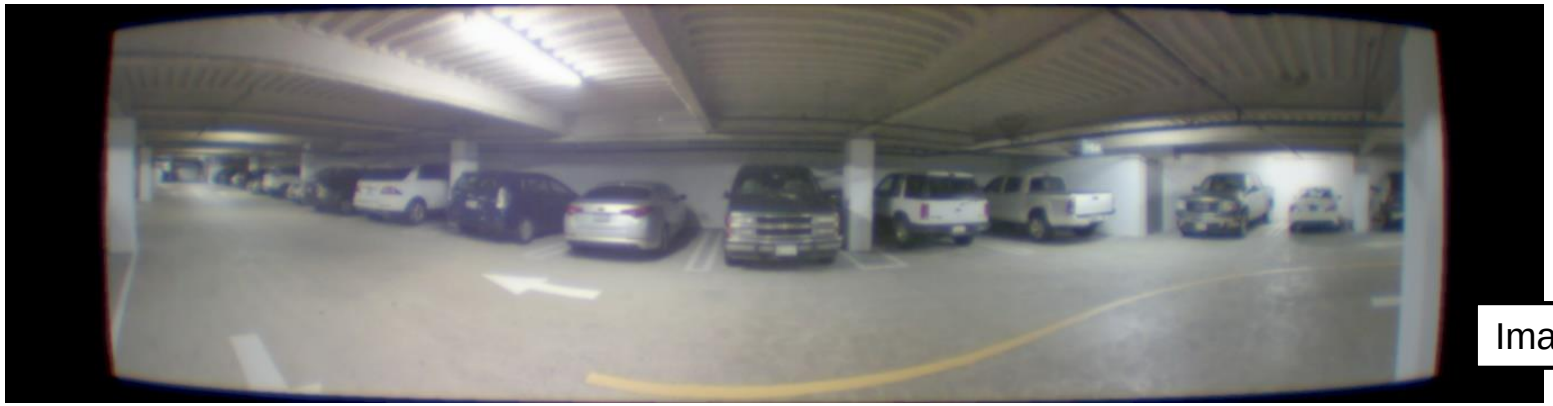
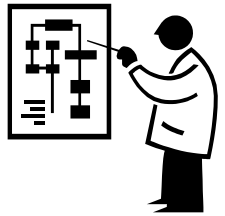
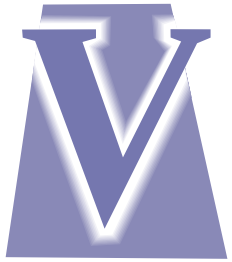


Image Simulation Result

Lateral color, and image blurring are clearly visible

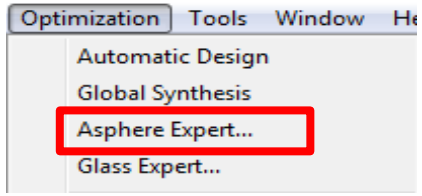
Design Process





Improve Performance with Asphere Locations Selected Using Asphere Expert

Using Asphere Expert

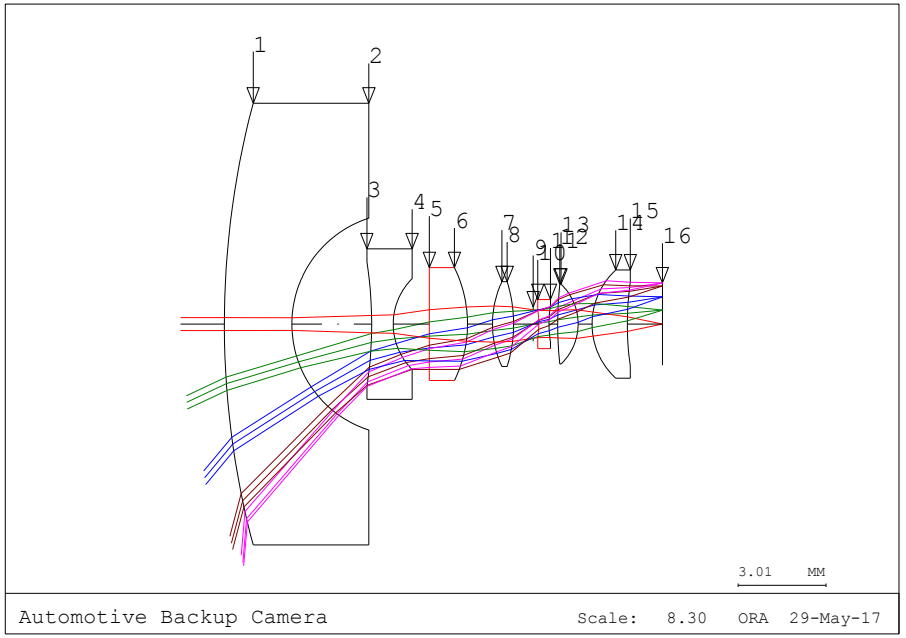


- Asphere Expert will rank the relative benefit of aspherizing each spherical surface in the lens
  - Computation time is equivalent to 1 optimization cycle, no matter how many surfaces are analyzed
  - Constraints & smart filters are supported, such as limits on aspheric slope departure, maximum permitted aspheric order, concave/convex limits, surface numbers, etc.

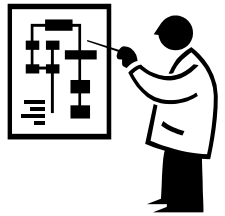
```
Determining optimal asphere location...



  NUMBER OF      SURFACE NUMBER   OPTIMIZED MERIT
ASPHERES ADDED   OF NEW ASPHERE   FUNCTION VALUE    ELAPSED TIME
--------------   --------------   ---------------   ------------
      0                -            14.0203509      00:00:00
      1               10             4.6639852      00:00:01
      2                5             3.1592893      00:00:04
```



Design Process



Find Real Glasses with Glass Expert

Glass Expert Automates the Traditional Glass Selection Process

- Uses an algorithm developed by Synopsys' ORAEngineering
- Iterates the following steps:
  - Replace a material
  - Optimize
  - Accept or reject the result based on:
    - Optical performance
    - Bulk absorption
    - Cost
    - Weight
    - Thermal expansion

For this system, we will allow it to select from among any of the Rochester Precision Optics (RPO) molded glasses

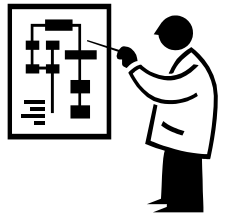
Before Glass Expert:

Glass
620410.603236
620410.603236
755201.275795
571995.631300
755201.275795
620410.603236
505724.684796

After Glass Expert:

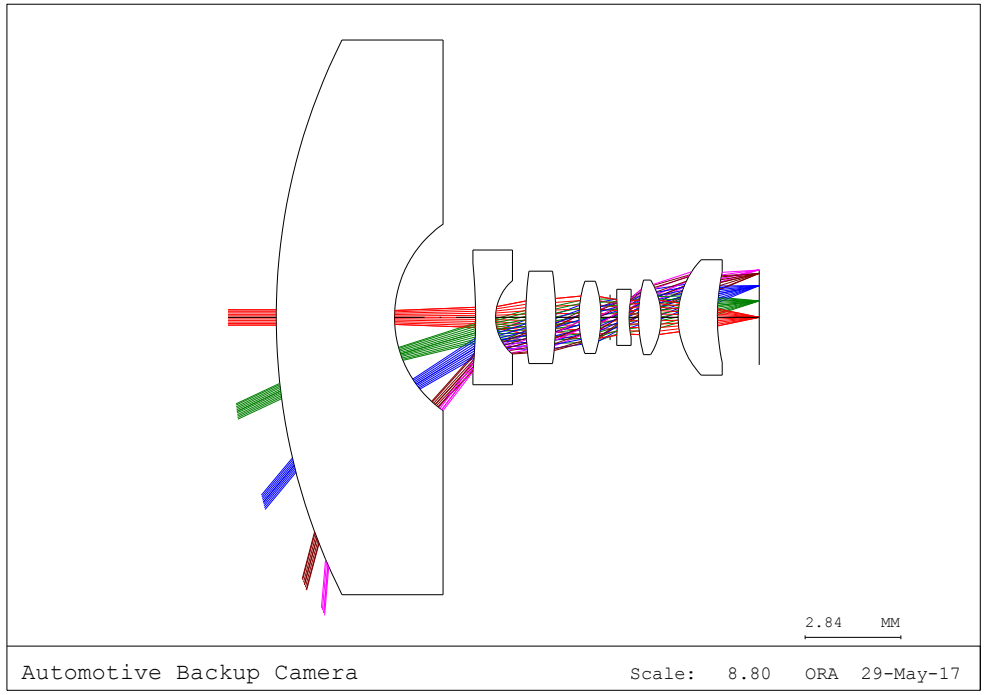
Glass
'TAF1'
'BSM16C'
'EFDS1'
'SLAL18'
'EFDS1'
'NFK51'
'NFK51'

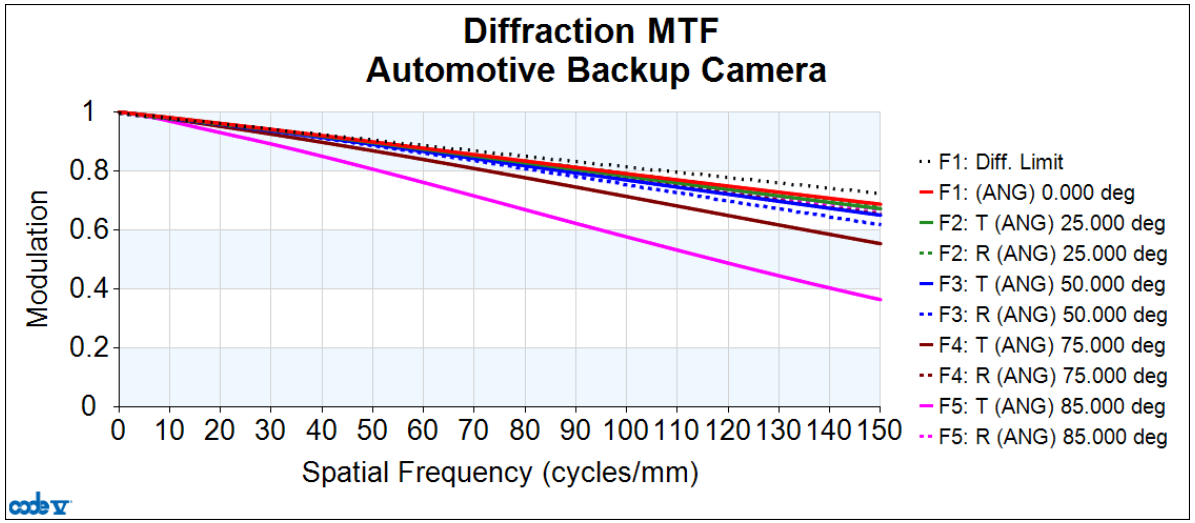
Design Process

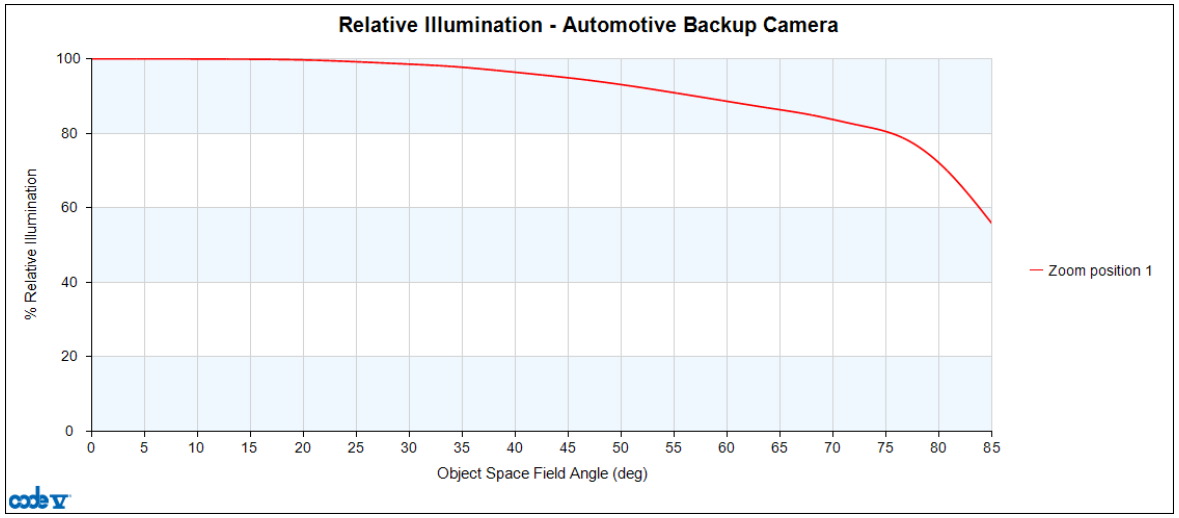


Evaluate Final Performance

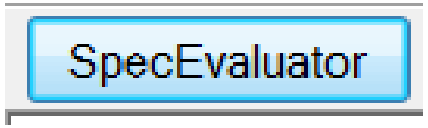
Final System Nominal Performance







Evaluate Final System against Specs:



SpecBuilder - Backup_Camera.sgt

SpecEvaluator

Specifications and Goals Table

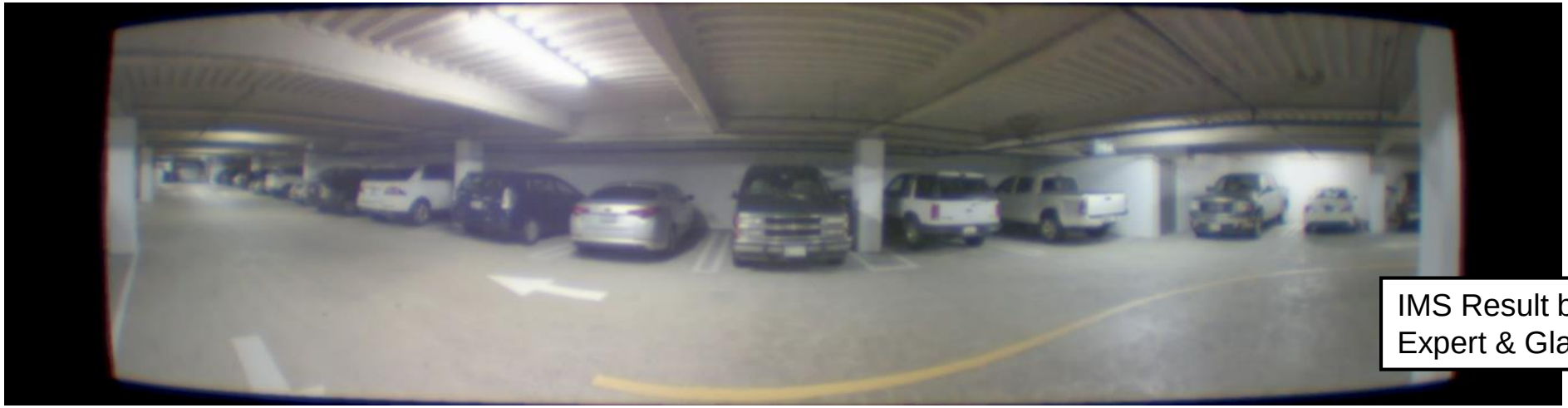
Label	Name	Goal Mode	Target	Value	Notes
	Effective Focal Length (mm): individual values over ZA F1; direction - mean of X & Y	display only		1.1230	
	Number of Elements	display only		7.0000	
	Number of Aspheric Surfaces: individual values over ZA	display only		2	
	F-number (First Order): individual values over ZA F1; direction - mean of X & Y	less than or equal to	2.5000	2.5000	
	Image Diameter (mm): Chief Ray Based	equal to	2.8000	2.8000	
	Field of View (Full-FOV, deg): individual values over ZA; direction - Y	equal to	170.0000	170.0000	
	Overall Length to Image (mm): individual values over ZA	less than or equal to	15.0000	14.3239	
	Surface Diameter (mm): individual values over ZA; overage scale factor = 1.020000	less than or equal to	15.0000	[1.1155, 14.9937]	
	Image Clearance (mm): individual values over ZA; relative to the last physical; overage scale fact	greater than or equal to	1.0000	1.0942	
	Relative Illumination (percent): individual values over ZA FA	greater than or equal to	50.0000	[55.6893, 100.0000]	
	MTF (at 150.000 cycles/mm or cycles/afocal units): individual values over ZA FA DA; azimuth - m	display only		[0.5182, 0.6860]	
	MTF (at 150.000 cycles/mm or cycles/afocal units): average over ZA FA DA; azimuth - mean of 0	display only		0.6244	
	MTF, As-Built (at 75.000 cycles/mm or cycles/afocal units, Mean + 2-sigma probability): individu	greater than or equal to	0.2500	[0.2828, 0.7541]	
	MTF, As-Built (at 75.000 cycles/mm or cycles/afocal units, Mean + 2-sigma probability): average	greater than or equal to	0.5000	0.6411	
	Aspect Ratio (Diameter/Center Thickness): individual values over refracting elements excluding fl	in the range (inclusive)	2.0000, 10.0000	[2.3631, 5.5136]	
	Aspect Ratio (Diameter/Edge Thickness): individual values over refracting elements excluding fla	in the range (inclusive)	2.0000, 10.0000	[2.7205, 5.9815]	

All Specifications are met.

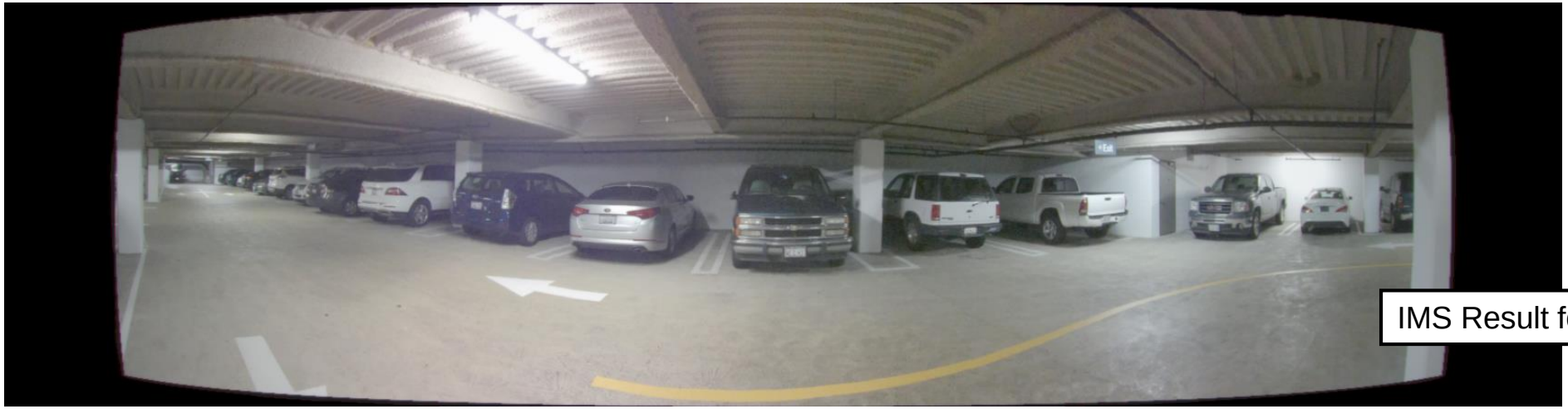
The loss in MTF with tolerances is significant (⚠ - icon), but the design meets all the specifications and goal.

Image Simulation

- The improvement in performance is easily seen with Image Simulation (**IMS**)



IMS Result before Asphere Expert & Glass Expert



IMS Result for Final System

Conclusion

- We have taken a patent lens starting point and developed a manufacturable, compact, high performance objective suitable as an Automotive backup camera

- Additional steps could include:
  - Reduction in the # of lenses (perhaps with the introduction of additional aspheric surfaces)
  - Use of Global Optimization to optimize for an inherently tolerance insensitive design form
    - The use of tolerance sensitivity constraints in optimization did greatly improve the as-built performance for this lens form, but these constraints are even more effective when the form of the lens is allowed to change significantly with global optimization