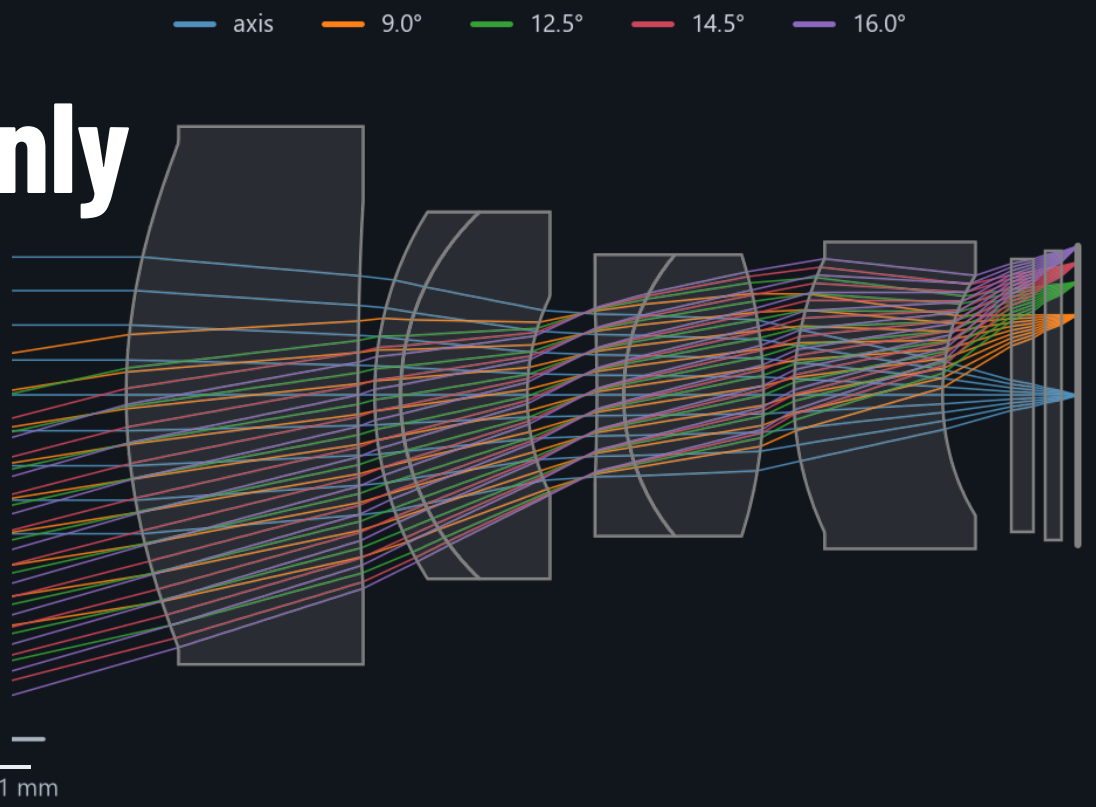
PARAXIAL CAPABILITY STUDY · FOUR CASE STUDIES · OCTOBER 2026

Camera optics for a car that sees with cameras only

Fifteen cameras and five lenses for an L2/L3 electric car with no lidar or radar: a far stereo pair to 250 m, a mid ring all around to 100 m, short-range fisheyes, an up-looking garage camera and two cabin cameras. Lens design, coverage, sun and headlamp glare, night SNR, heat, cold, rain and grime, all through the Paraxial API.



55 px
across a car at 250 m
in each far camera

100.0 %
of the band around the car
seen by the mid ring at 100 m

38×
less sun glare, coated and edge-blackened

1.3×
far-lens focus drift, in depths of focus, −40… +105 °C

Every number is a saved Paraxial API response or simple arithmetic on one. The lenses start from published design forms, re-optimised for public automotive sensors and shop limits; the car and its requirements are generic.

BACKGROUND

A vision-only car, four studies

A car that drives on cameras alone has no lidar or radar to fall back on. Its cameras must resolve a car at 250 m ahead, see all around to 100 m, see the ground and a child beside the bumper, see a garage barrier overhead, and watch the people inside, through a raked windshield, into the sun, at night, from −40 to +105 °C and in the rain.

The question: can one platform take these cameras from published lenses to a constellation, a glare budget and a weather qualification, with scripts that reproduce every number?

> Every number is a saved Paraxial API response or simple arithmetic on one. The lenses start from published design forms, re-optimised for public automotive sensors and shop limits; the car and its requirements are generic.

CS1 · Five lenses

Far stereo, mid ring, short-range fisheye, occupant and driver monitor, each fixed-focus for its working distance; tolerances for the far lens.

CS2 · The constellation

13 exterior and 2 cabin cameras on a generic EV: coverage, blind zones, pixels on target, stereo depth.

CS3 · Sun, glare and night

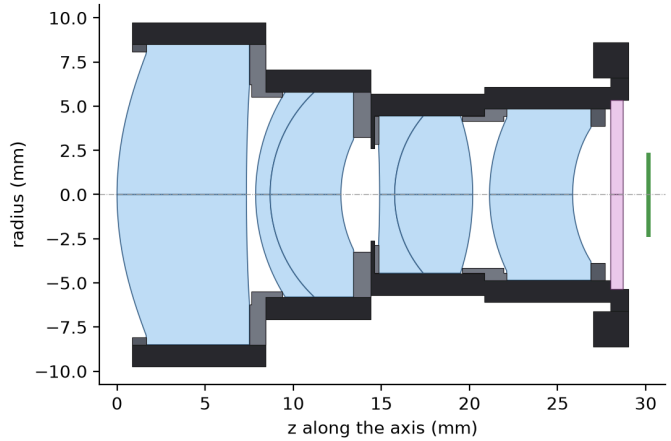
The far lens behind a 63° windshield: sun in and out of the picture, oncoming headlamps, a pedestrian by low beam.

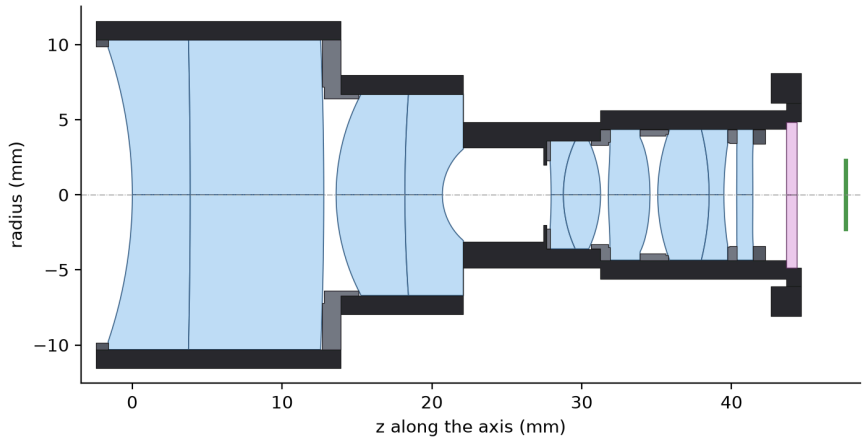
CS4 · Heat, cold, rain, grime

Five lenses from −40 to +105 °C with fixed focus; drops, rain and road film on the windshield; fog.

Five lenses a shop can make, each in its own housing

- **Made to be ground:** 4 of 5 lenses pass every shop rule with 0.5 mm flat lands: glass edge ≥ 0.8 mm, centre ≥ 0.8 mm, air edge ≥ 0.3 mm. Each sits in a barrel cut from its STEP export, with seats, spacers, a stop diaphragm and a retainer, checked solid against solid.
- **Far stereo:** a six-element Double Gauss with two moulded aspheres, 16.100 mm; MTF 0.70 on axis and 0.55 at its worst field, at half Nyquist. It keeps 80 % of its 250 m axis MTF for objects from 50 m out.
- **Mid ring:** ten elements with a moulded field corrector at f/2.4, 5.760 mm; 0.72 on axis, 0.55 at the 60° corner.

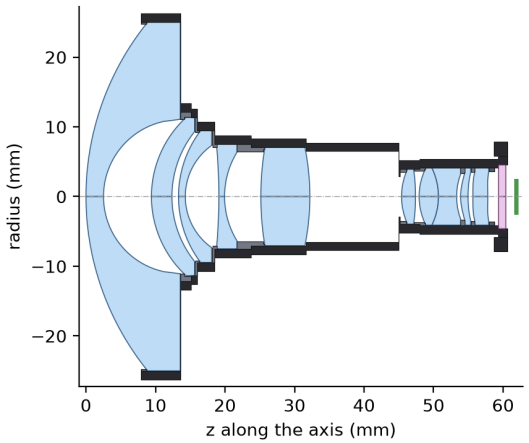


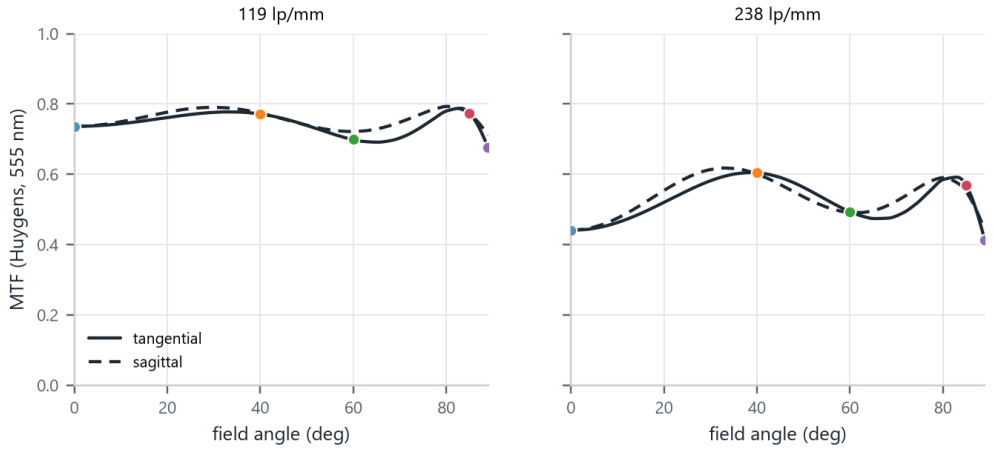


Sharp cabin lenses; the wide corners are the limit

- **Fisheye** to 89°: 0.66 on axis, 0.38 at its worst field.
- **Cabin, at 940 nm:** occupant 0.72 on axis and 0.67 at worst; driver monitor 0.78 and 0.75.
- **Far-lens tolerances** (120 from the API's budget), back focus as the compensator: RSS +150 % commercial, +70 % precision; refocus travel under 30 µm. Monte Carlo (200 builds, not refocused): 95th percentile +316 % commercial, +98 % precision.

> **Next:** lift the mid and fisheye corners to the 0.40 goal, and loosen the far lens's leading tolerance (S9 decenter y).

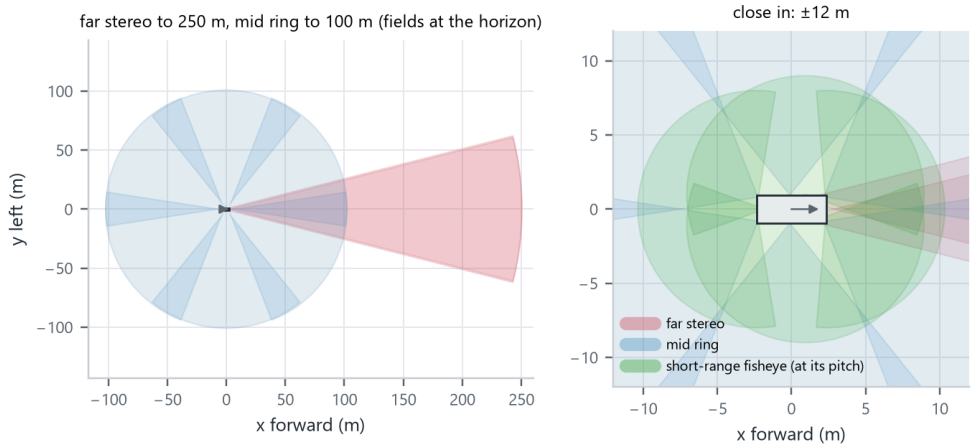


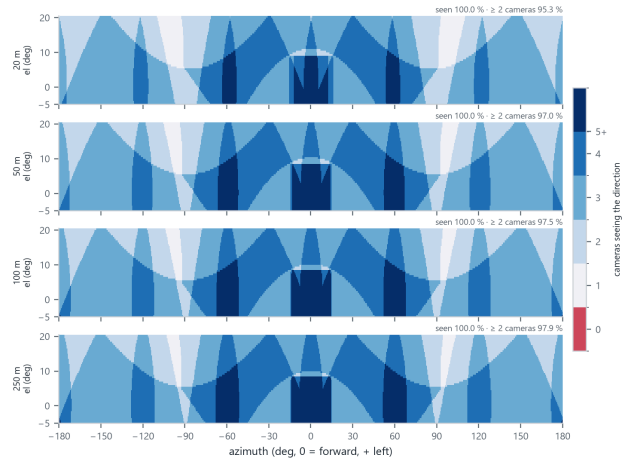


CASE STUDY 2 · THE CONSTELLATION, PART 1

Fifteen cameras, every direction covered

- **Mid ring at 100 m:** 100.0 % of the −5/+20° band around the car; the whole set sees 100.0 % of it at 20 m.
- **Pixels on target:** 55 px across a car at 250 m, 49 px at 100 m in the mid ring.
- **Fields from the lenses:** each camera's view is its CS1 lens's real chief-ray mapping from the API, not a nominal field angle.

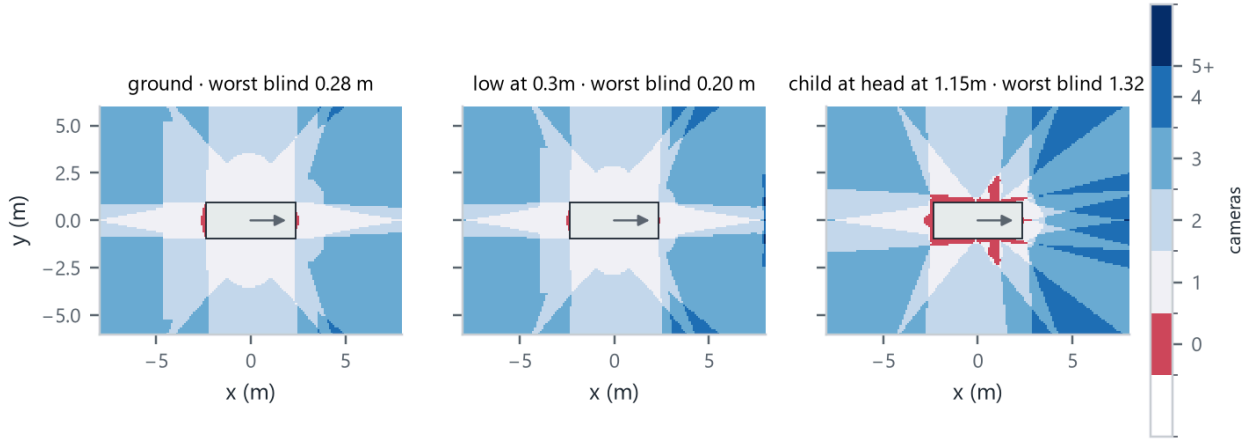


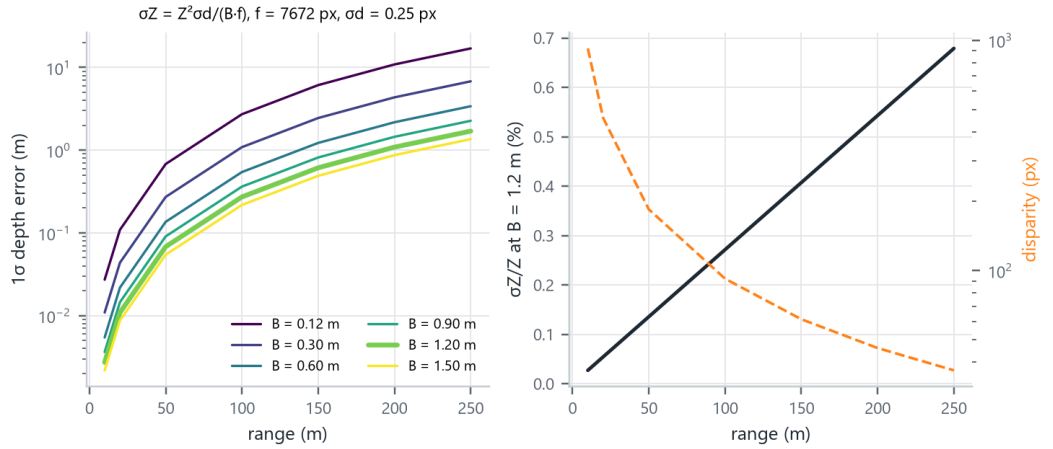


Stereo depth to 250 m; a child can hide by the door

- **Stereo** on a 1.2 m baseline: depth error 1.7 m (0.7 %) at 250 m.
- **Blind zones:** the ground gap next to the body is 0.28 m, but at child height 1.32 m: the side fisheyes look down, not out.
- **Garage barrier:** seen 0.25 m ahead by the up-looking camera. **Cabin:** 5 of 5 seats in frame; 71 px across the driver's eye.

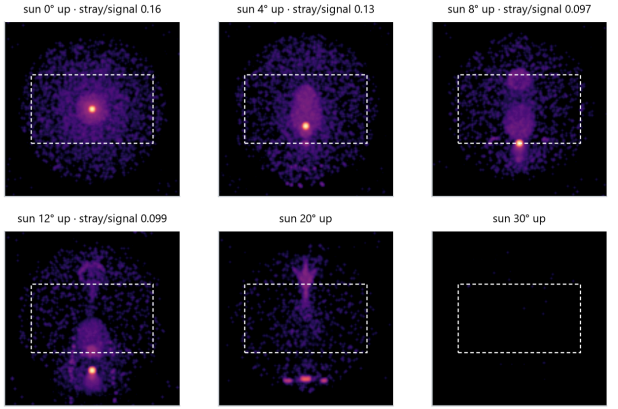
> **Decision:** tilt the mirror fisheyes up, or add a B-pillar camera, to close the child-height gap.



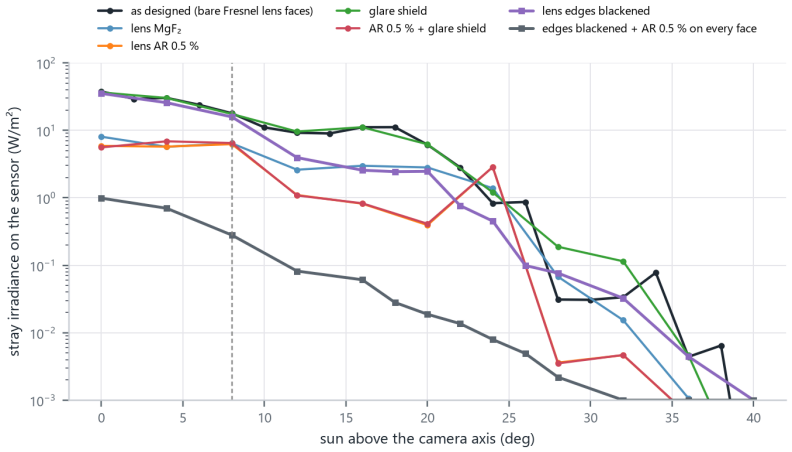


The windshield is harmless; uncoated lens faces are not

- **Windshield** (63° laminate): axis MTF 0.82 against 0.78 for 95 % of the bare lens; double image 0.93 %.
- **Sun in the picture:** uncoated, the stray light is 373 % of a sunlit white target, almost all of it ghosts between lens faces; with the sun above the picture, 110 %.
- **Fix:** AR on every face and blackened edges: 5.3 % in the picture, 0.3 % above it. A glare shield does nothing.

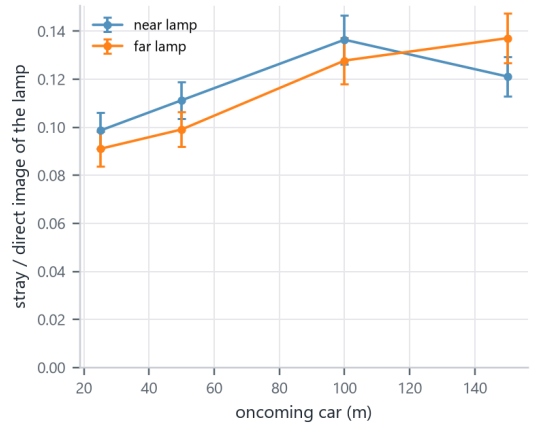


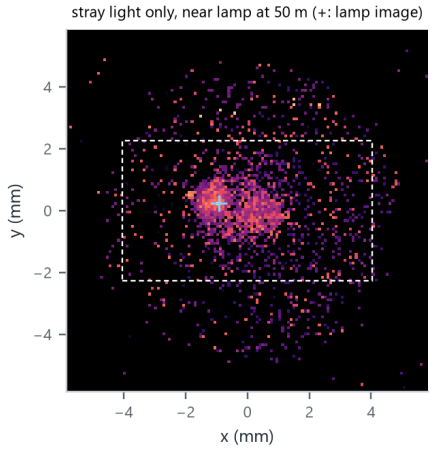
Log irradiance on the image-plane pad (5 decades), direct image plus stray, 200,000 rays per frame, smoothed 0.7 px, one scale for all six; dashed: the sensor. The sun leaves the picture above 8°.

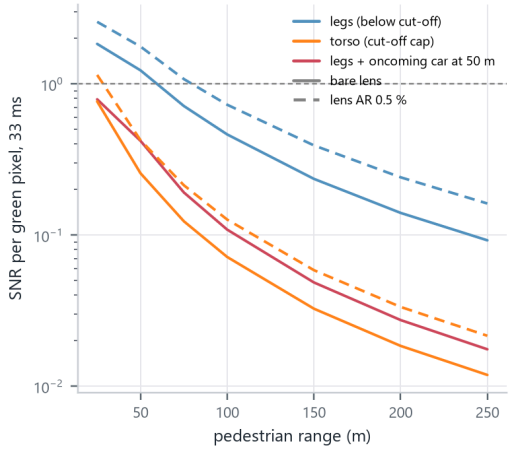


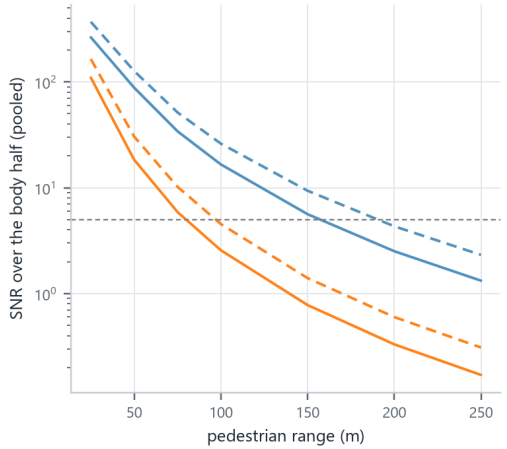
Low beams light a pedestrian to 150 m; the torso is the limit

- **Oncoming low beams** 25–150 m: stray light 0.137 of the lamp image at most, a halo, not a veil.
- **Pedestrian in dark clothing,** this car's low beams only: the legs reach a pooled SNR of 26 at 100 m; the torso, above the beam cut-off, 4.5.
- **Oncoming car at 50 m:** the legs' per-pixel SNR at 50 m stays at 0.74.







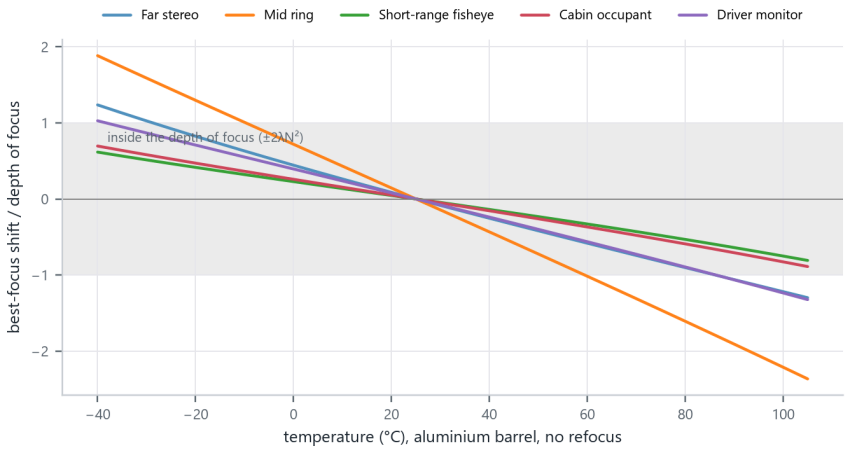


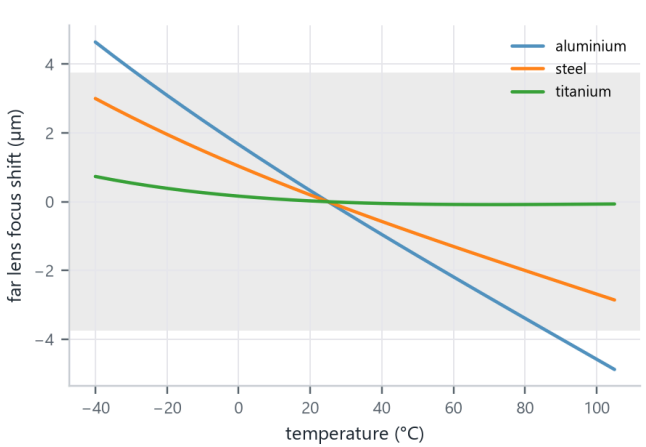
CASE STUDY 4 · HEAT, COLD, RAIN AND GRIME, PART 1

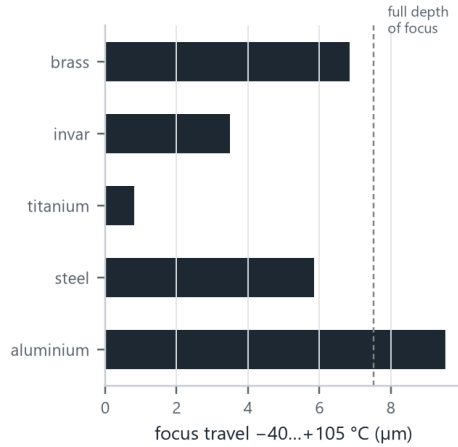
A titanium barrel holds the far lens; the others drift 0.8–2.4× in aluminium

- **Far lens** in an aluminium barrel: focus moves 4.9 µm (1.3×) over −40…+105 °C against ±3.8 µm ($\pm 2\lambda N^2$); its axis MTF at the worst temperature is 0.63.
- **Barrel material:** titanium, 0.8 µm of travel with the best of the API's five metals, against 7.5 µm (full depth).
- **Mid ring** 15.8 µm (2.4×), fisheye 3.6 µm (0.8×), occupant 7.2 µm (0.9×), driver monitor 10.8 µm (1.4×).

> **Decision:** titanium for the far lens; run the same barrel sweep for the other four before their barrels are chosen.

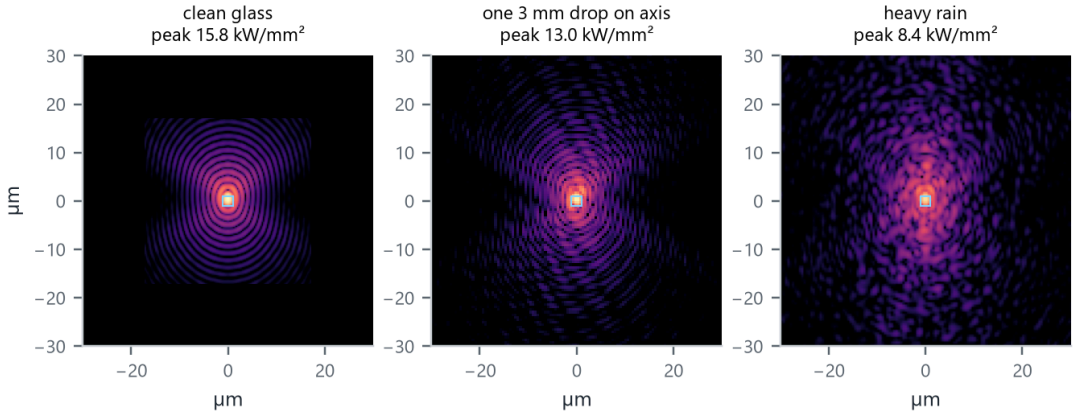




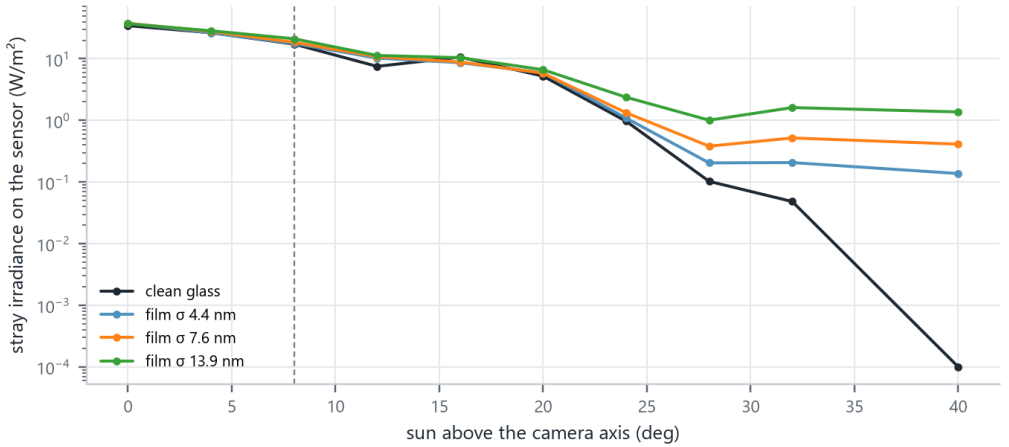


Rain dims the image; fog sets the speed

- **Rain on the windshield** (NSC drops): the far camera's PSF peak keeps 87 % in light rain, 64 % in moderate and 53 % in heavy rain; the drops throw light out of the image rather than blur it.
- **Road film** keeps 96 % of the peak but multiplies sun glare from outside the picture.
- **Fog:** below 326 m visibility a 250 m target drops under 5 % contrast; no lens recovers it.



Log irradiance, same scale in all three; the blue square is one 2.1 μm pixel.



SUMMARY · REVISION 2 → REVISION 3 · SAME FIVE CAMERAS, SENSORS AND FIELDS

Revision 3 can be centred, spaced and seated; the cost is glass, length and more glare

Manufacturability

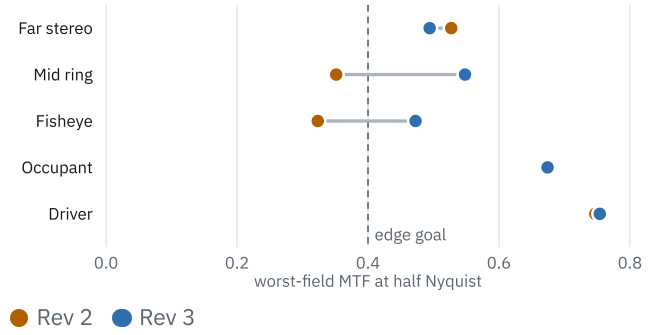
sd/|R| at the polished edge ≤ 0.75 convex, ≤ 0.85 concave; air gaps ≥ 0.5 mm, stop ≥ 0.3 mm; OD : CT ≥ 2 (common/mfg_rules.py, revision 3 rules on both)

STEEPEST FACE SD/|R| (LIMIT)	REV 2	REV 3		
Far stereo	1.00	0.73	(0.75)	met
Mid ring	0.79	0.76	(0.85)	met
Fisheye	1.00	1.00	(1.00)	met (cup)
Occupant	0.85	0.83	(0.85)	met
Driver	0.80	0.74	(0.85)	1 short

Resolution

Polychromatic FFT MTF at half Nyquist, worse of T and S, 31 field points, CS1

MEAN MTF ACROSS THE FIELD	REV 2	REV 3	
Far stereo	0.62	0.62	same
Mid ring	0.47	0.61	higher
Fisheye	0.53	0.62	higher
Occupant	0.70	0.71	higher
Driver	0.76	0.77	higher



Downstream

The far lens behind the windshield (CS3; stray as % of a sunlit white target), −40 to +105 °C and rain (CS4)

FAR LENS, DOWNSTREAM	REV 2	REV 3	
Sun above picture	25 %	110 %	4.4× more
Sun in picture	214 %	373 %	1.7× more
Low beams (≤ 0.10)	0.092	0.137	fails
Focus shift	1.3× DOF	1.3× DOF	same
Moderate rain, peak	63 %	64 %	same

Steepness and gaps ↔ glass and length

Shallower faces and real gaps took 43 → 44 elements across the five lenses and 219 → 244 mm of total track; the closest air gap went 0.12 → 0.52 mm. Revision 2 has 32 shortfalls under the new rules.

One exception: the fisheye cup

The fisheye catches 85–89° through a hemispherical cup on its front element (sd/R 1.00), kept by decision: a chamfered rim and a flat annulus, L1 held between two threaded retaining rings, and the top and bottom of the 89° beam lost at the cup's equator.

Mounting ↔ how glass is made

Convex faces run to the edge on square-cornered spacers and rings, concave faces end in a ground bevel, moulded aspheres keep a flange; every barrel loads from both ends against a stop shoulder, with STEP files and an overlap check for all five.

A truer windshield, a harsher glare count

CS3 now traces a curved one-piece windshield with the lens barrel and 200,000-ray sun frames; the glare numbers rose with the model as much as with the lens (part of the 16–22° band is light entering the cut edge of the modelled glass patch, an upper bound), and the low-beam halo now fails its 0.10 goal.

SUMMARY

Fifteen cameras, five lenses, one platform

STUDY	SUBJECT	HEADLINE	CHECKS
CS1	Five lenses	`Far MTF 0.70, mid 0.72 on axis; 4 of 5 meet shop rules; far tolerance RSS +150 %`	18 ✓ · 1 ◐ · 1 ✗
CS2	Constellation	`100.0 % ring coverage; 55 px at 250 m; child gap 1.32 m`	14 ✓ · 0 ◐ · 1 ✗
CS3	Sun, glare, night	`Glare 373 % → 5.3 %; legs SNR 26 at 100 m`	4 ✓ · 2 ◐ · 4 ✗
CS4	Heat, cold, weather	`Far focus 4.9 µm (1.3×); moderate rain 64 % of peak`	6 ✓ · 3 ◐ · 2 ✗

One model, end to end

The CS1 lenses set the CS2 fields, went behind the CS3 windshield into the sun and the night, and through CS4's heat and rain.

Glare, found and fixed

Path attribution split the glare into lens ghosts and an edge path; coated and edge-inked variants removed both, and showed what a glare shield cannot do.

Reproducible

Every number comes from an API response saved with the script that made it; statuses are computed, not typed.

Fast

Four studies in 15.7 h of agent time, the lens redesign and re-runs 8.7 h of it; API jobs ran for 17.4 h, several at once.

Every number is a saved Paraxial API response or simple arithmetic on one. The lenses start from published design forms, re-optimised for public automotive sensors and shop limits; the car and its requirements are generic. Platform issues found along the way are listed in each INTERNAL report and in CASE_STUDIES_README.md.