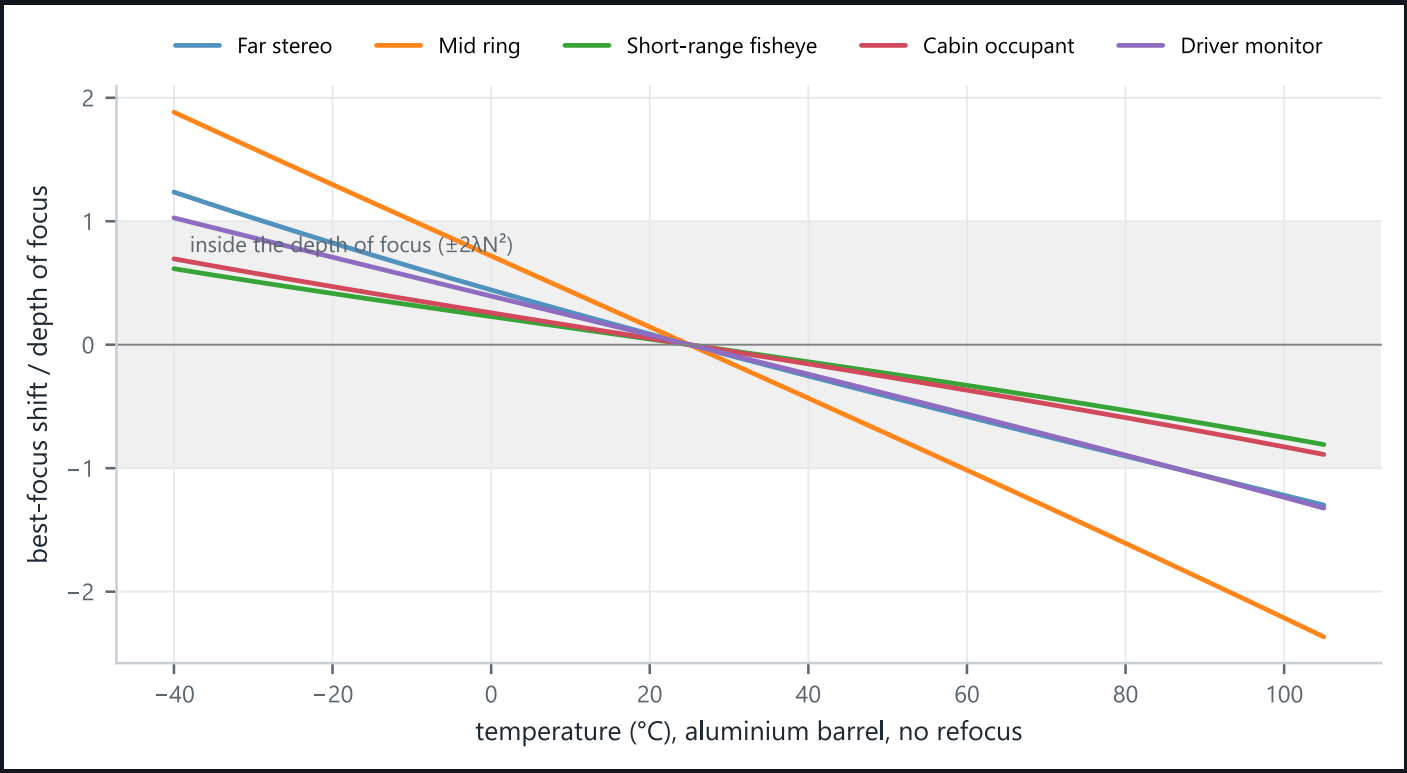
CASE STUDY 4 · VISION-ONLY CAR · 31 OCTOBER 2026

Heat, cold, rain and grime: what the weather does to the image

A car's cameras live from a frozen night at −40 °C to a parked noon at +105 °C behind the glass, and they look through whatever is on the windshield. This study runs the five CS1 lenses through that temperature range with the focus fixed, as built, and puts rain drops, a wet windshield and a road film in front of the far stereo camera in its non-sequential model. Every optical number comes from the Paraxial API.



Best-focus shift against temperature for the five lenses in aluminium barrels, in units of each lens's own depth of focus (thermal analysis, Paraxial API).

1.3×
the far lens's focus shift at the temperature extremes, in depths of focus

36 %
PSF peak lost behind moderate rain (15 % of the glass wet)

326 m
fog visibility below which a 250 m target falls under 5 % contrast

Paraxial · fea deployment · project “Vision-Only Car Demo”

TEMPERATURE 01

From a frozen night to a parked noon

The thermal analysis rebuilds each lens at −40, +25, +85 and +105 °C: every radius and thickness grows with its glass's expansion, every index moves with its catalog dn/dT, the aluminium barrel spaces the elements and the sensor, and the focus stays where the factory set it at 25 °C. The tolerance on focus is the diffraction depth of focus $\pm 2\lambda N^2$ at each lens's primary wavelength and working f/# (local arithmetic on the CS1 paraxial result).

LENS	DEPTH OF FOCUS ± (MM)	LARGEST SHIFT (MM)	× DEPTH	AXIS MTF 25 °C	−40 °C	+105 °C	API ATHERMAL METHOD
Far stereo	3.8	4.9	1.3	0.76	0.73	0.63	PassiveAthermalization
Mid ring	6.7	15.8	2.4	0.67	0.26	0.41	HousingMatching
Short-range fisheye	4.5	3.6	0.8	0.65	0.63	0.64	PassiveAthermalization
Cabin occupant	7.6	7.2	0.9	0.63	0.49	0.63	PassiveAthermalization
Driver monitor	7.9	10.8	1.4	0.71	0.50	0.64	HousingMatching

Far stereo, short-range fisheye, cabin occupant and driver monitor stay within 1.5× their depth of focus in aluminium. Mid ring moves 2.4–2.4× the depth of focus at the extremes, focus moving toward the lens as it warms. At +105 °C, a car parked in the sun, the far lens's axis MTF at half Nyquist falls from 0.76 to 0.63.

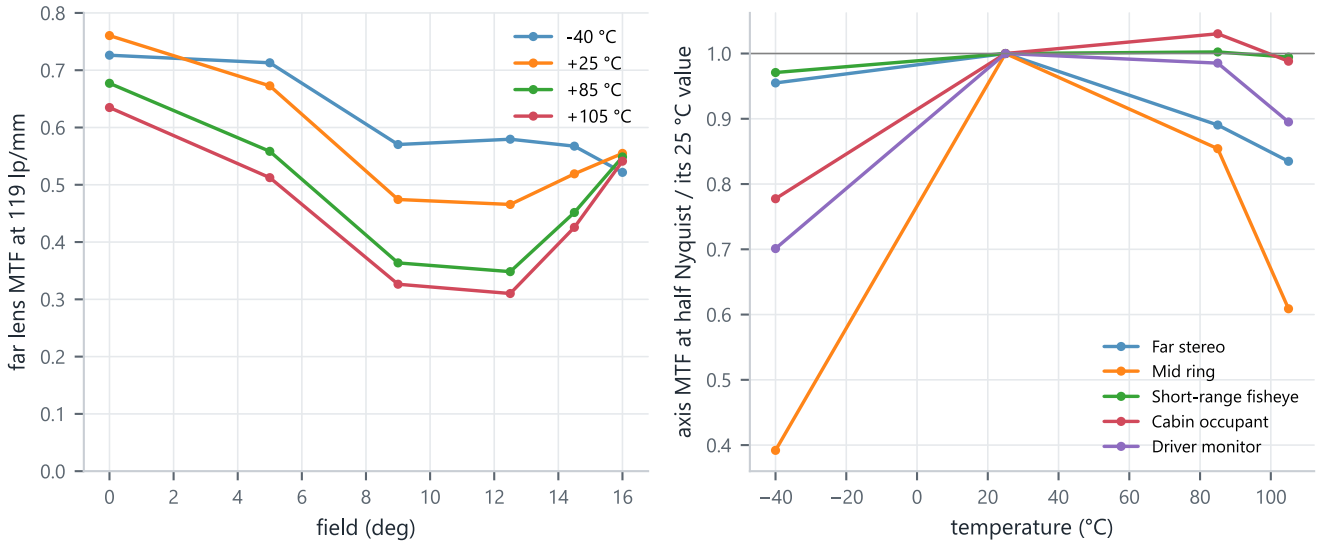


Figure 1. Left: far lens MTF at 119 lp/mm across the field at the four temperatures. Right: each lens's axis MTF at half Nyquist relative to 25 °C.

Barrel material

The thermal-compare analysis swaps the far lens's barrel for the API's other materials. The best, titanium, leaves 0.8 µm of travel against a 7.5 µm full depth and athermalizes the lens. The API's focus travel is linear in the barrel's expansion coefficient; a straight-line fit through its five materials puts the zero-shift barrel at +8 × 10^{-6}/K (local arithmetic), inside the range of ordinary metals.

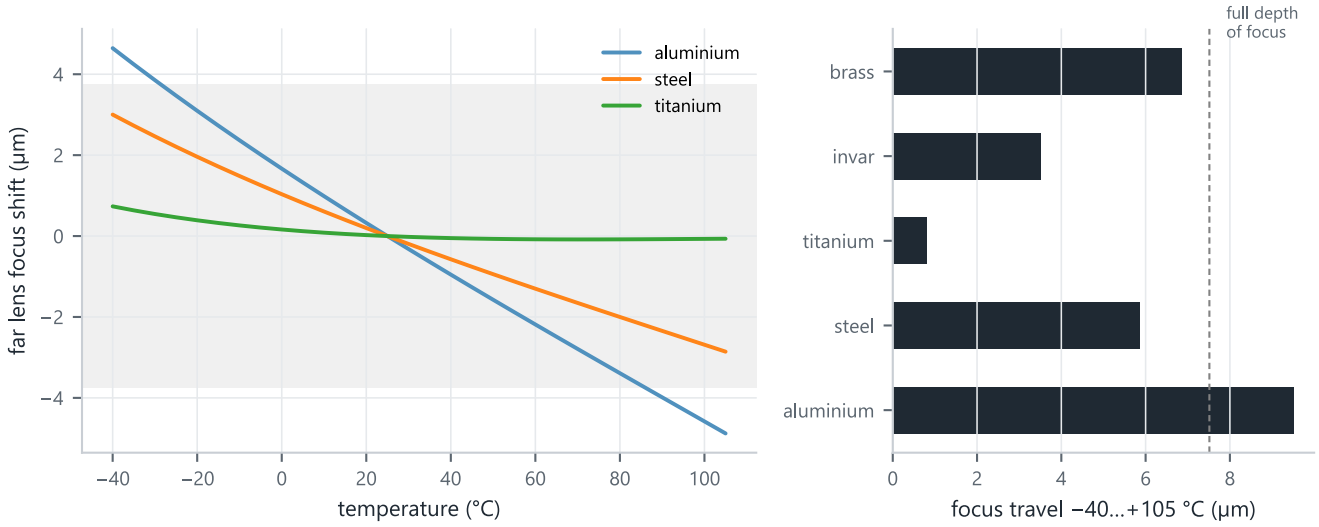


Figure 2. Far lens focus shift for three barrels (grey band: ±2λN²) and the travel for all five of the API's barrel materials.

RAIN AND GRIME 02

What the windshield carries

The far camera behind the windshield is promoted to its non-sequential model, and each case gets its own copy, with the lens barrel as absorbing scene objects. The windshield is CS3's curved one-piece glass. A drop is a spherical cap of water seated on its curved outer face (on the biconic sag, its axis along the local normal), with the footprint and the contact angle setting its height: 45° for weathered, untreated glass and 85° for a rain-repellent coating (decisions). Rain fields scatter non-overlapping drops of 0.5–2.5 mm over the patch of glass both fields look through, to 5, 15 and 30 % wet area. Every drop stays off the two fields' chief rays: a single drop sits just beside the on-axis chief ray (its edge 0.25 mm from it, across the car), and a rain field keeps each drop 0.2 mm clear of both, because the PSF is centred on the chief ray and a drop on it would throw that ray, and the centre, off the image (platform notes). The road film is a Harvey-Shack scatter model on the outer face with the roughness raised to 4.4, 7.6 and 13.9 nm rms, a stand-in for grime, not a measured dirt BSDF. The metric is the API's coherent NSC PSF at 555 nm: its peak, Strehl ratio and the coherent power that still reaches the image.

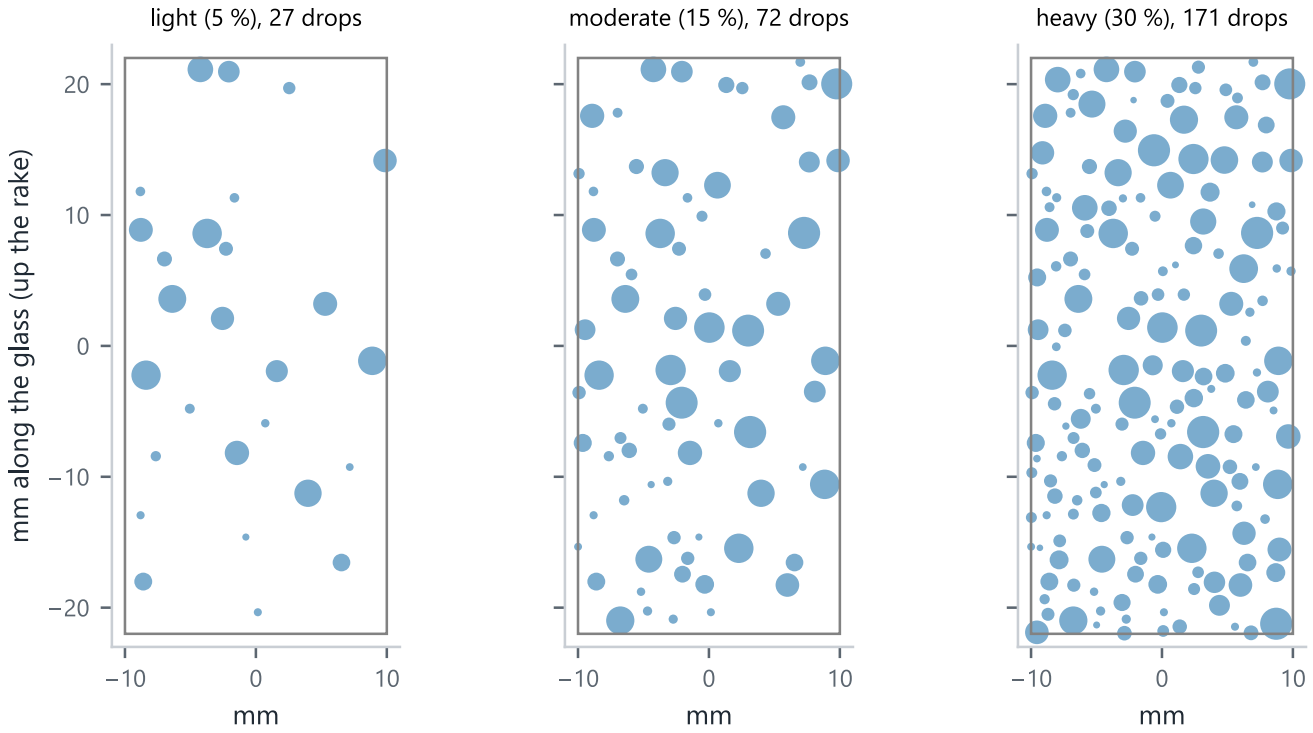


Figure 3. The three rain fields on the glass patch in front of the far camera (fixed seed).

CASE	DROPS	PEAK, ON AXIS	PEAK, 12.5°	STREHL, ON AXIS	COHERENT POWER, ON AXIS
clean glass	0	100 %	100 %	0.929	100 %
one 1 mm drop	1	98 %	100 %	0.927	99 %
one 2 mm drop	1	92 %	100 %	0.925	96 %
one 3 mm drop	1	82 %	100 %	0.920	91 %
one 2 mm drop, coated glass	1	89 %	100 %	0.925	94 %
light rain (5 % wet)	27	87 %	104 %	0.922	93 %
moderate rain (15 %)	72	64 %	97 %	0.905	81 %
heavy rain (30 %)	171	53 %	72 %	0.890	74 %
moderate rain, coated glass	72	48 %	95 %	0.918	70 %
road film σ 4.4 nm	0	100 %	100 %	0.929	100 %
road film σ 7.6 nm	0	99 %	98 %	0.929	99 %
road film σ 13.9 nm	0	96 %	93 %	0.929	98 %

The drops do not blur the image so much as dim it: the Strehl ratio barely moves while the peak and the coherent power fall together, because each drop is a strong little lens that throws the light it intercepts far outside the image of the point. Moderate rain takes 36 % of the on-axis peak and heavy rain 47 %; that light becomes a veil over the rest of the picture. The rain-repellent coating's taller drops are

stronger lenses and do worse standing still (48 % against 64 %): the coating earns its place by shedding the drops at speed, which a static model cannot show. The road films change the PSF by a few percent at most: grime matters through veiling glare, not sharpness.

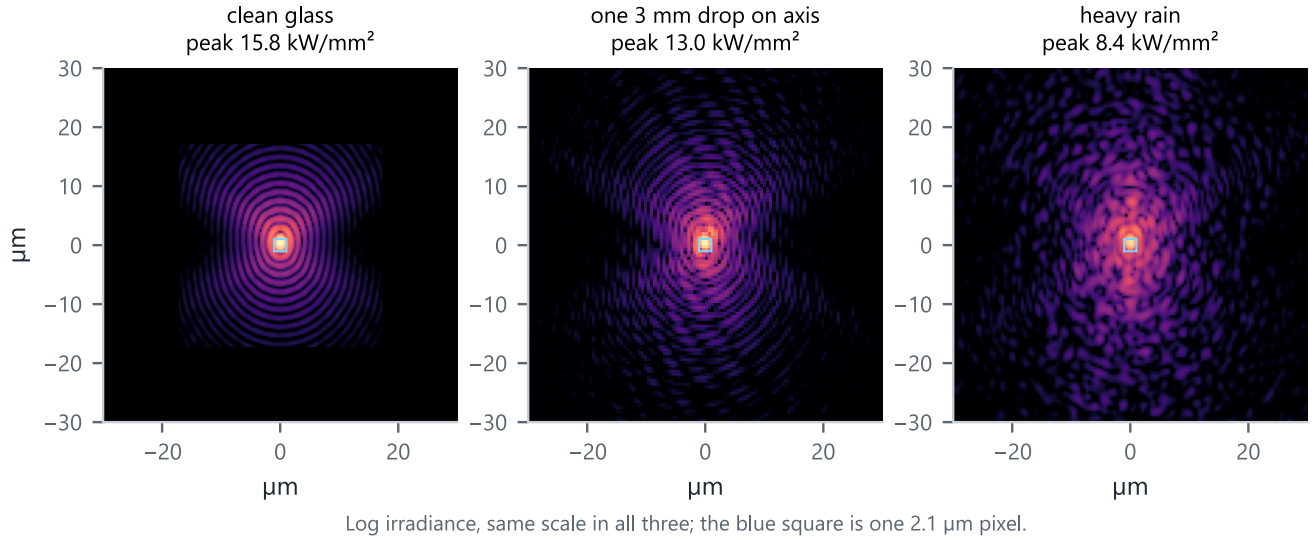


Figure 4. The far camera's on-axis PSF through clean glass, one 3 mm drop and heavy rain (NSC coherent PSF, 555 nm).

Road film and the sun

With the sun on the axis the stray irradiance on the sensor is 34.5 W/m² through clean glass and 36.9 W/m² through the heaviest film: the uncoated lens's own ghosts dominate there (case study 3). Out of the picture the film is what matters: with the sun 40° above the axis it raises the stray light from none (no traced ray reaches the sensor through clean glass) to 1.37 W/m², because it scatters sunlight forward into the lens that clean glass would let pass by. Once the lens is coated and its edges blackened (case study 3), a dirty windshield becomes the largest source of sun glare.

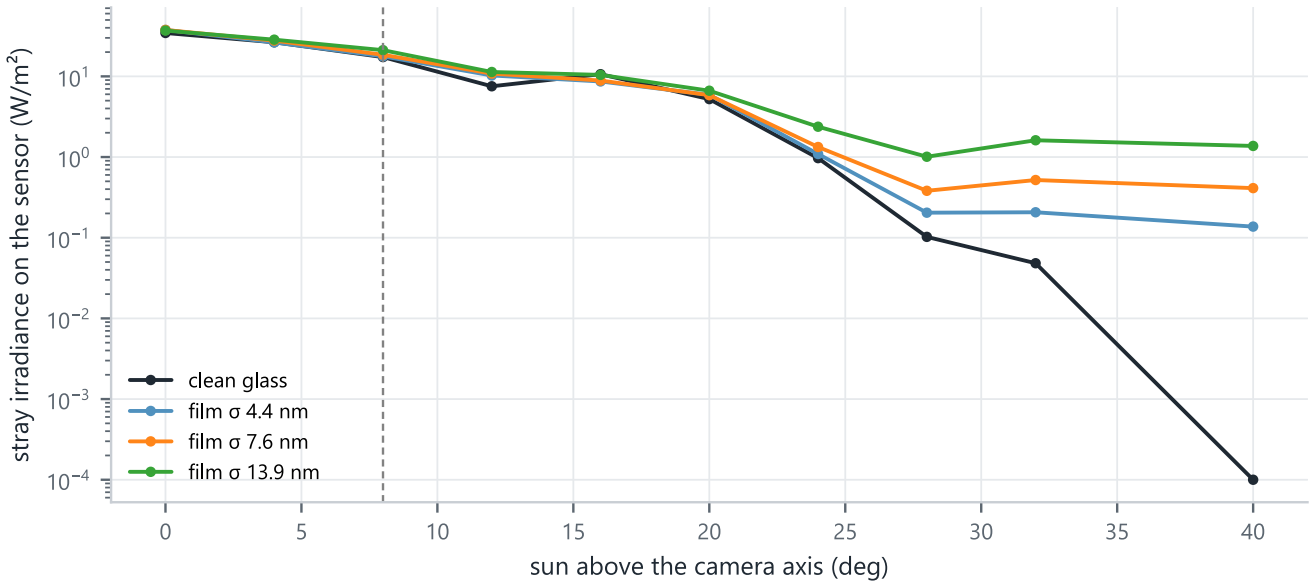


Figure 5. Stray irradiance on the sensor against sun elevation, clean glass and three road films (sun-in-field, visible band, uncoated lens).

FOG 03

The air sets the range

Fog is a property of the air, not of the optics, so the API is not needed: by Koschmieder's law a target at distance d keeps a fraction exp(−3.912 d/V) of its contrast in fog of meteorological visibility V. With 5 % as the faintest contrast the perception stack uses (a decision), the visibility each range needs is:

TARGET RANGE	VISIBILITY NEEDED
50 m	65 m
100 m	131 m
150 m	196 m
250 m	326 m

Fog is visibility below 1 km, so in fog the far cameras' 250 m reach is lost first and the car must slow to the range its cameras still see; no lens change recovers it. A vision-only car's fog policy is a speed policy.

RECOMMENDATIONS 04

What the design should do about it

- **Match the barrel to the lens.** A titanium barrel holds the far lens to 0.8 µm of travel over −40…+105 °C. The barrel sweep was run for the far lens only; mid ring (2.4–2.4× in aluminium) need the same sweep before their barrels are chosen.
- **Keep the glass in front of the far pair clear.** A heated, wiped zone is worth more than any lens change: moderate rain costs a third of the PSF peak. The windshield heater and defrost are outside the API's reach and are not modelled here.
- **Treat grime as glare.** Road film barely touches the PSF but multiplies the sun glare from outside the picture; keep the camera's patch of glass washed, like the headlamps.
- **Fog is a speed limit.** Below about 326 m visibility the far range is gone whatever the optics.

METHOD 05

How the numbers were made

Every optical number is a saved Paraxial API response; the full report adds the method detail.