PARAXIAL

Shallow roof light bar: optical and thermal design study

Federal Signal demonstration | study FS-LIGHTBAR-001 | requirements v1.0 | designs D1 and D2 | 02 November 2026

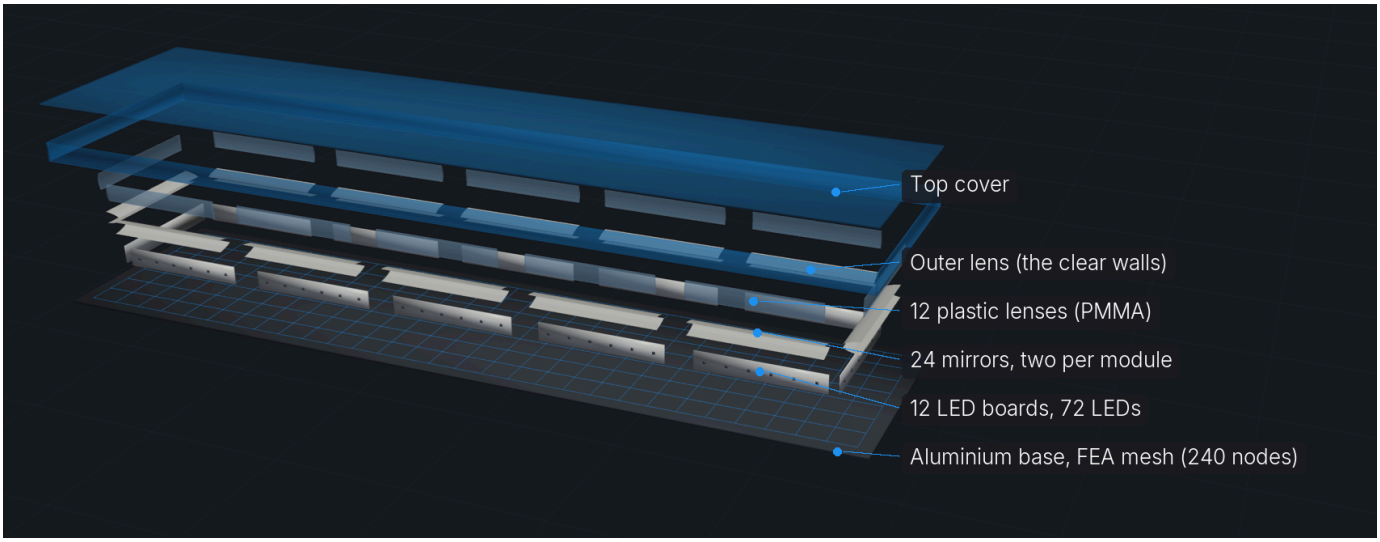
Simulation study prepared for Federal Signal. Every number in this report is simulated with Paraxial's non-sequential optics engine and FEA solver, coupled by an AI agent working in the Paraxial API. The light bar is a synthetic representative design built from the stated assumptions (section 2 and appendix B), not a Federal Signal product, and the angular mask is synthetic: nothing here is an SAE J595 or J845 result. No Federal Signal data was used; Federal Signal part data, measurements and photometric requirements would replace the assumptions.

The study in plain terms

The question. Can a roof light bar only 33 mm tall be bright enough in every direction a driver could be in, and stay inside its temperature limits, from a -40 C winter to an 85 C roof in full sun? This study answers that in simulation for a representative bar, designed and simulated in the Paraxial API. An AI agent working in the API traced 174 candidate module designs in three families in 18 minutes, then solved the light (ray tracing) and the heat (FEA) together for the finalists, because each affects the other: hot LEDs give less light, and light absorbed inside the bar becomes heat.

Yes, in simulation. The reflector + lens design (C1) meets every requirement in all five weather cases at 52 W average, about half the 100 W budget. Two numbers are tight: on the hot roof the plastic lens runs 1.0 C under its 85 C limit, and at this lowest-power setting the blue light has only 0.5% more than it needs.

Then we built a better version. The same simulation that says yes also shows exactly where the first design is fragile: on a hot roof its lens runs 1.0 C under its limit, and blue has so little light to spare that 80 of 100 simulated builds would fall short. Most of the lens's heat turns out to arrive through its mount from the LED board, so we changed one thing, an isolated lens mount, drove the LEDs harder (red 0.55 A, blue 0.45 A) and re-ran every check. The robust design, D2, meets every requirement with 19.3% more red light and 16.7% more blue than needed; none of the 100 simulated builds falls short, and the lens runs at 83.4 C, for 62 W average, still well under the 100 W budget. The result is most sensitive to how well a real roof cools the bar, which is a demonstration assumption here.

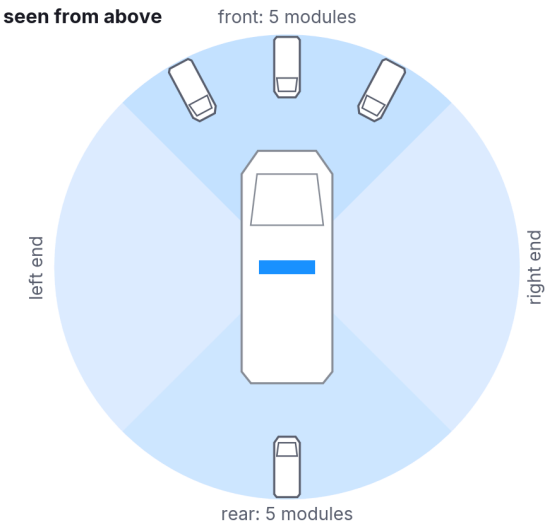


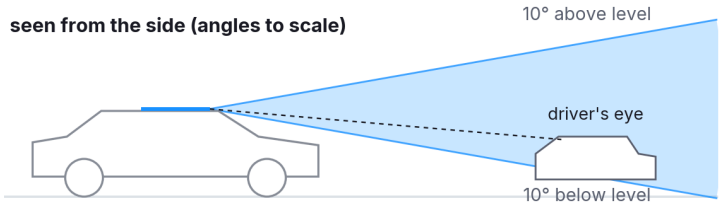
In plain terms: the whole bar model, taken apart so every part can be seen: the top cover and the clear outer lens, then in each of the 12 modules a plastic lens, two mirrors and an LED board with six LEDs, all on an aluminium base. Every part shown is in both the ray trace and the FEA. Exploded for clarity (layers lifted 45 to 270 mm); in the model they sit as assembled. Modules: 5 front, 5 rear, 1 at each end. The base shows its 240-node FEA mesh. Geometry from the study's model documents, designed and simulated in the Paraxial API.

THE JOB: BE SEEN FROM EVERY DIRECTION A DRIVER COULD BE IN

req v1.0 · synthetic mask, not SAE

A roof light bar must be bright enough all the way around the vehicle, and from a little above to a little below level.







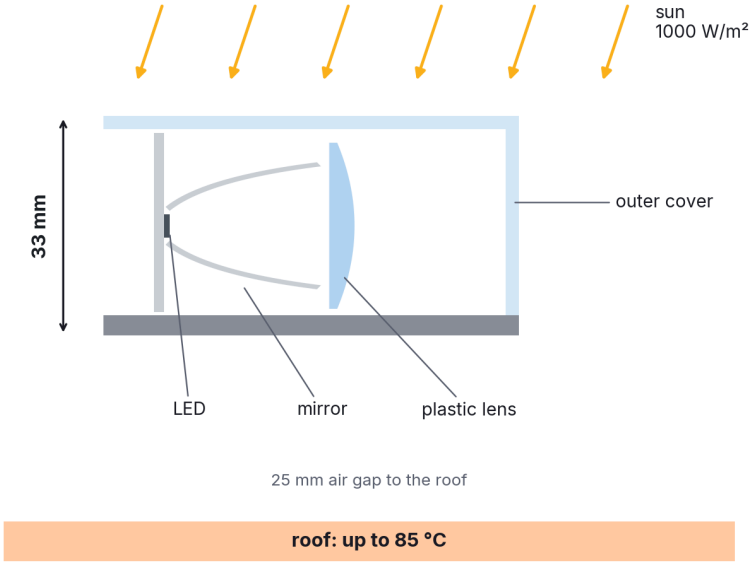
Each must reach at least 110% of its target brightness:
red 150 cd in the centre (large dots), 75 cd at the edges (small dots).

What the bar has to do. Left: the 12 modules (5 front, 5 rear, 1 at each end) each cover 45 degrees either side of where they face, so together they cover all the way around the vehicle. Right: the light must reach from 10 degrees below to 10 degrees above level, and each module is checked in 35 directions against a target brightness. The targets are a synthetic demonstration mask, not SAE J595 or J845.

WHAT MAKES IT HARD

study_spec v1.0 · module C1 section

The bar is only 33 mm tall, sits on a roof that can reach 85 °C in full sun, and has a power budget.



LED chips

must stay below 105 °C, and give about 10% less light on a hot roof than in a 25 °C room

Plastic lens

must stay below 85 °C (it softens)

Cold

the same light is required at −40 °C

Power

whole bar: at most 100 W average, 200 W peak

Thin

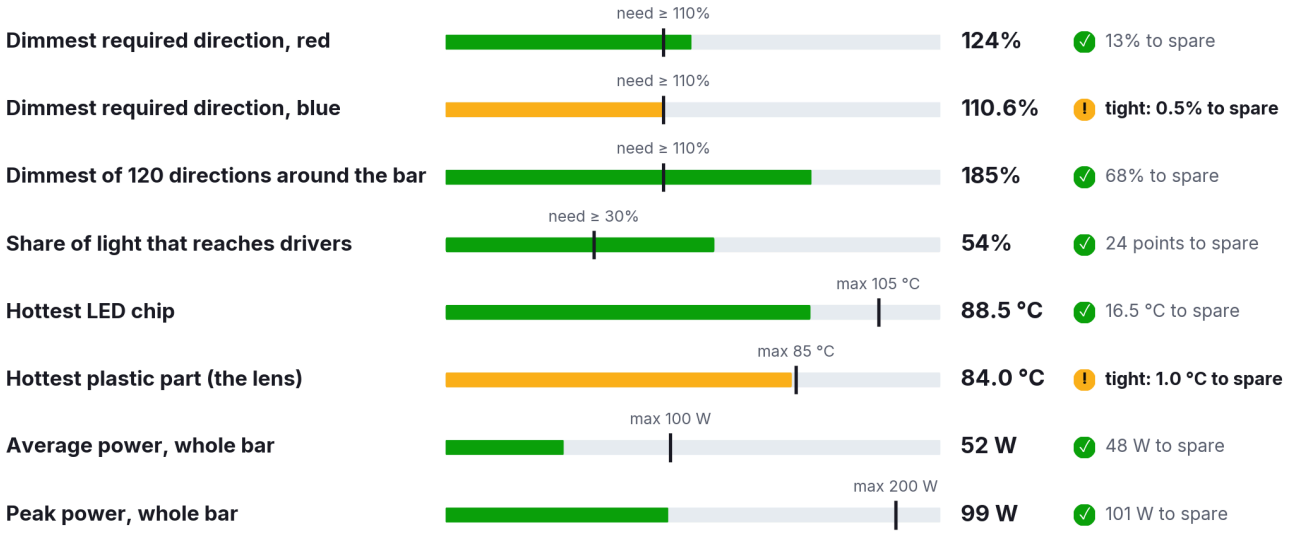
33 mm leaves little room to fold and aim the light

The real cross-section of the selected module (C1) inside the 33 mm bar, with the conditions it has to survive. Limits and conditions are the study's proposed demonstration values; Federal Signal values replace them when supplied.

THE ANSWER: THE REFLECTOR + LENS DESIGN MEETS EVERY REQUIREMENT

worst of T1–T5, both colours · optics + FEA

Worst case over all five weather cases (−40 °C to an 85 °C roof in full sun) and both colours, at red 0.5 A and blue 0.375 A per LED.



Every requirement for the selected design, worst case over all five weather cases (T1 cold -40 C, T2 room 25 C, T3 hot shade 65 C, T4 hot roof 85 C + 1000 W/m2 sun, T5 hot roof with forced cooling) and both colours. Brightness is the lower 95% bound of the simulated value, as a percentage of the target. Simulated: optics Paraxial non-sequential engine, heat Paraxial FEA solver.

Why it works

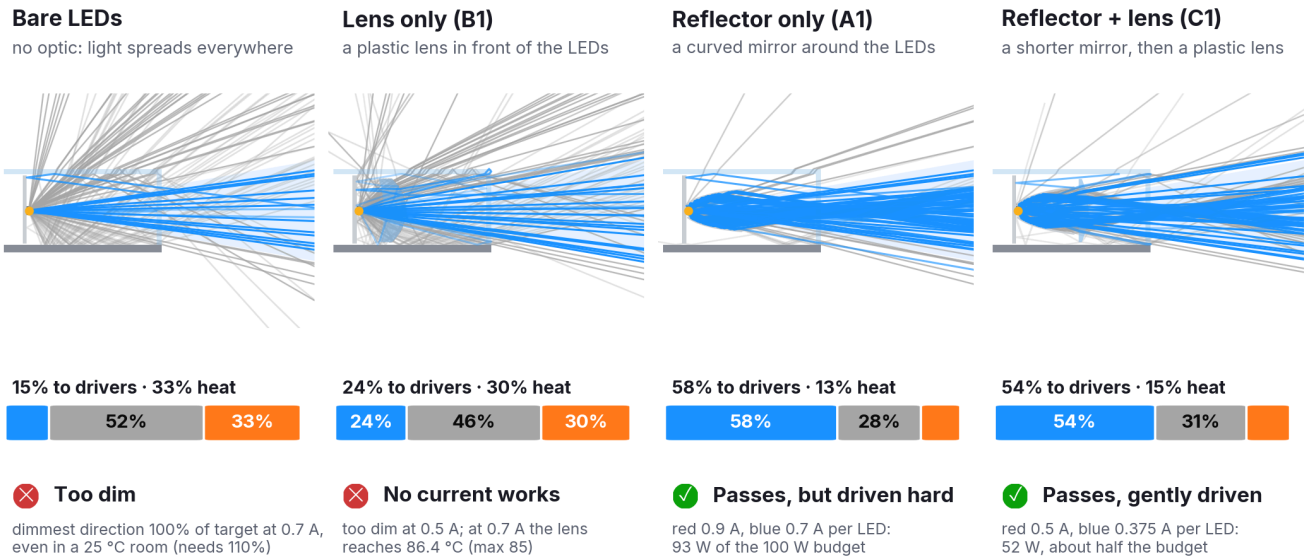
A bare LED throws light in every direction, so most of it misses the narrow band drivers are in. A lens in front catches only the light already heading forward. A curved mirror catches the sideways light and turns it forward, but on its own it bunches the light into two bands just above and below level and leaves level itself dim. The C1 design uses a shorter mirror followed by a lens: the mirror gathers the light and the lens fills in the band at eye level.

That is the chain that makes it work. More of the light lands where it is needed, so the LEDs can run at a lower current (red 0.5 A instead of 0.9 A for the reflector-only design). Lower current means less heat, and less heat keeps the plastic lens under its limit on the hot roof. The C1 design passes on 43% less power than the only other design that passes.

WHY THE REFLECTOR + LENS DESIGN WORKS

nsc/trace · engine ray paths · full-sphere ledger

Real ray paths from the engine, one LED, side view. Blue rays leave toward drivers (within 10° of level); grey rays miss them.

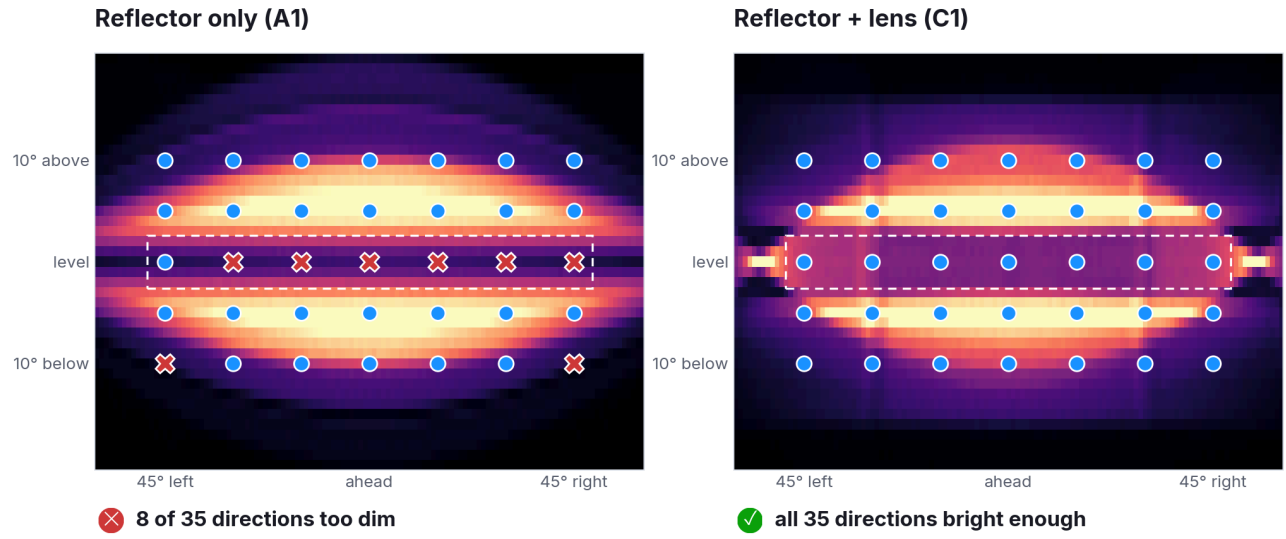


Top: real ray paths recorded by the Paraxial engine for one LED in each design (about 100 rays launched close to the section plane; side view). Bars: where all the light goes, from the full trace (25 seeds x 2 M rays per design, red, 0.7 A, 25 C). Bottom: the outcome of the coupled light-and-heat study. Simulated, Paraxial non-sequential engine and Paraxial FEA solver.

SAME LEDS, SAME 0.5 A, SAME 85 °C ROOF IN THE SUN

polar detector · 1×1° cells · scaled to the T4 LED output

The reflector alone leaves a dim stripe at eye level: 8 of its 35 directions fall short (6 of them level). Adding the lens fills it in: all 35 pass.

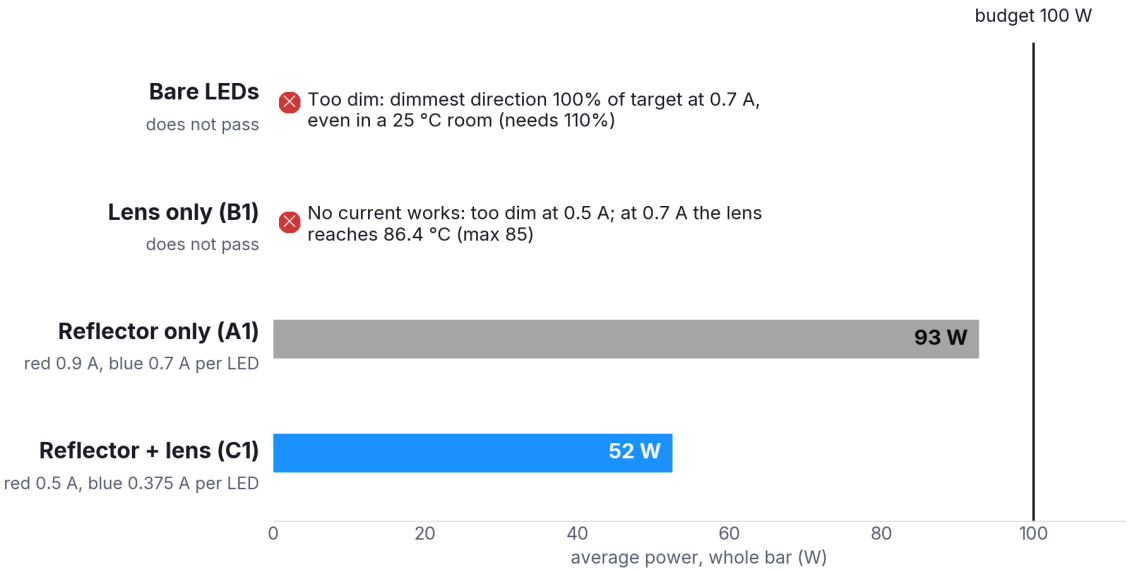


Map: how bright the module looks from each direction (brighter = more light). Dots: the 35 required directions; ● bright enough, × too dim (below 110% of its target). Dashed box: level, eye height. Engine trace at room temperature, scaled to this current and the hot-roof LED output.

Both designs at the same red current (0.5 A per LED) in the hot-roof case. Each map is the engine's traced brightness pattern scaled to the hot-roof LED output; dots are the 35 required directions, judged on the lower 95% bound against 110% of target. The reflector alone puts its light into two bands just above and below level and leaves level itself dim; the lens in C1 fills that in. Simulated, Paraxial non-sequential engine.

WHAT EACH DESIGN NEEDS TO PASS EVERYTHING, EVERYWHERE `coupled optical-thermal · T1–T5`

Average power for the whole bar at the lowest current that meets every requirement in all five weather cases.



The reflector + lens design passes on 43% less power than the only other design that passes.

Average power of the whole bar at the warning duty (100 ms on / 100 ms off), at the lowest evaluated current that passes every requirement in all five weather cases. Currents evaluated: 0.35, 0.5 and 0.7 A per LED for every design, plus intermediate and higher option points.

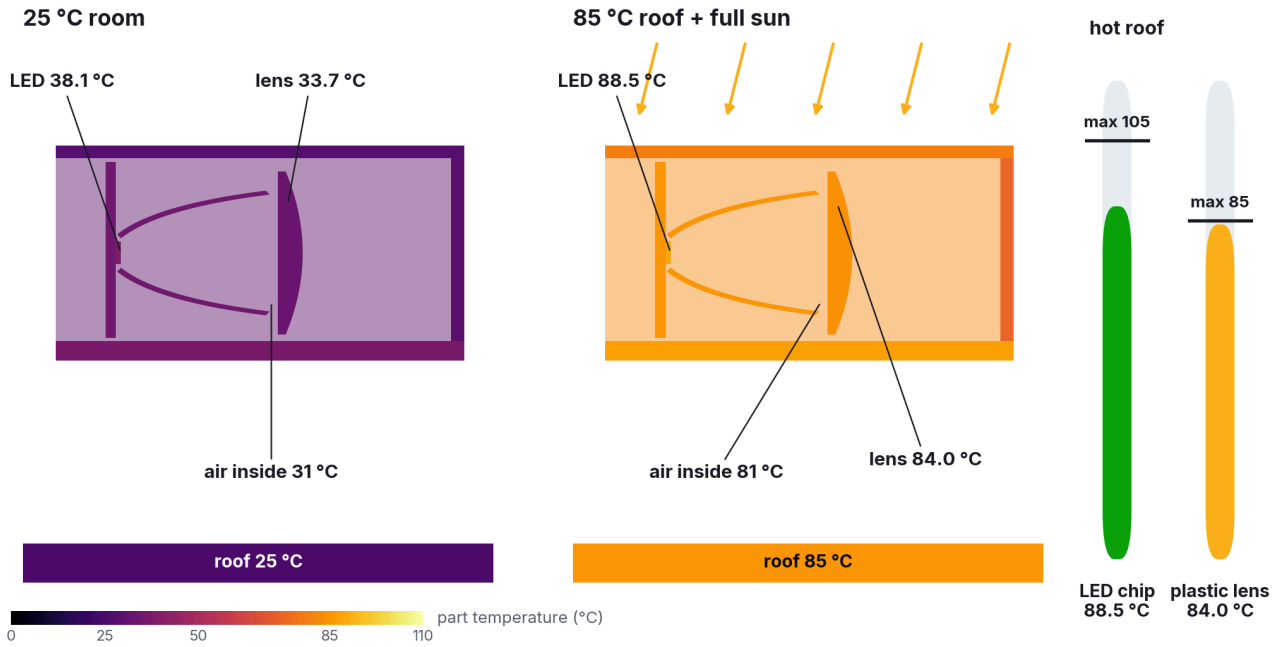
What heat does (FEA)

On the hot roof the air inside the bar reaches 81 C. The LED chips stay well inside their 105 C limit (88.5 C at the peak of a flash); the plastic lens, at 84.0 C, is the part closest to its limit. The LEDs also give about 10% less light when hot than in a 25 C room, and the study includes that loss.

WHAT HEAT DOES: THE SAME MODULE, ROOM VS HOT ROOF

FEA · solved node temperatures

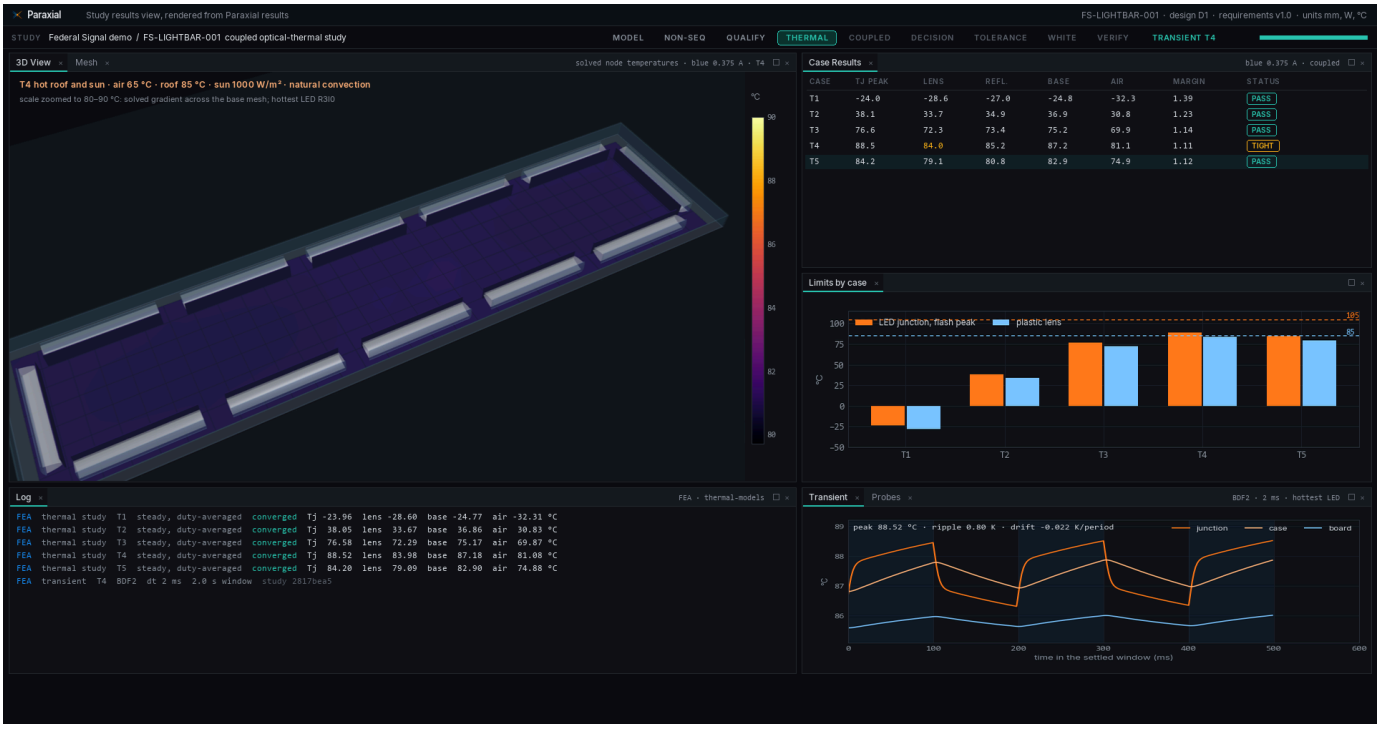
Blue LEDs flashing at 0.375 A (the hotter colour). Solved temperatures of each part; LED chip at its flash peak.



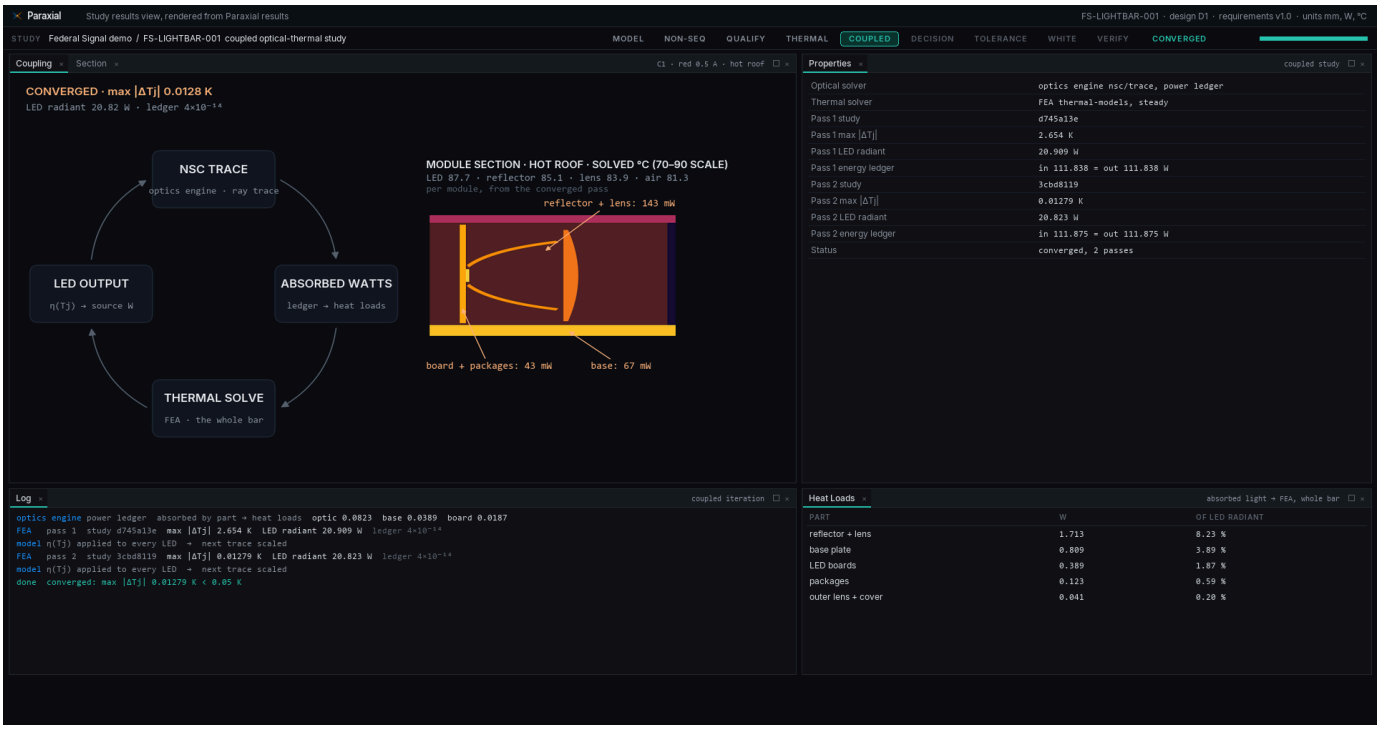
Solved temperatures of each part of the selected module, blue channel at its selected current, in the room case and the hot-roof case. LED chip: the peak during a flash; other parts: the steady state at the warning duty. Simulated, Paraxial FEA solver.

Light and heat, solved together: ray tracing and FEA

The heat side is a thermal model of the whole bar on Paraxial's FEA solver: the base plate as a 30 x 8 mesh (240 nodes, 442 conductors), the 72 LED packages as junction-case-board resistor networks, the drivers, controller and processor, and the sun, roof radiation and convection of each weather case. It is coupled to the optical trace. The trace's power ledger says how many watts of light each part absorbs, those watts are applied as heat, the solved junction temperature sets each LED's light output, and the loop repeats. On the hot roof it converged in 2 passes: the largest junction change fell from 2.65 K to 0.013 K, and the energy ledger closes to 4e-14.



The thermal stage of the study as it ran (frame from the study film). The bar's thermal model on Paraxial's FEA solver: the base plate as a 30 x 8 mesh (240 nodes, 442 conductors) carrying the solved node temperatures, the 72 LED packages as junction-case-board resistor networks coloured by junction temperature (colour scale zoomed to 80-90 C to show the gradient). Right: the solved result of each of the five cases with its status, the junction and lens against their limits per case, and the hottest LED through three settled 100 ms flashes. Below: the solver log. Blue channel at 0.375 A; Paraxial FEA solver.



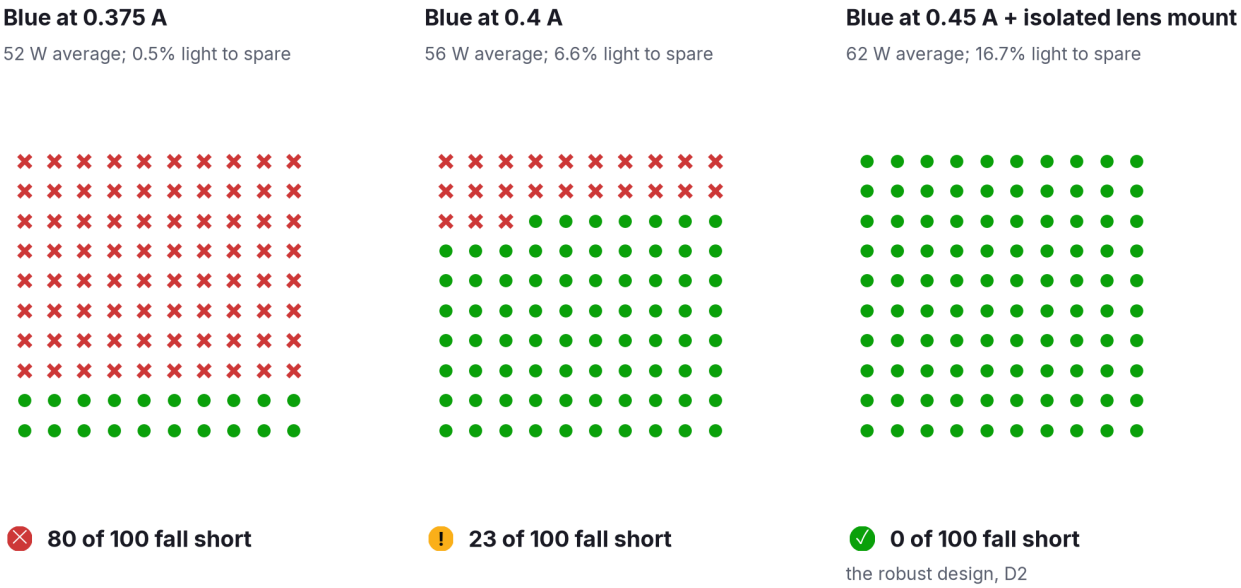
The coupled stage as it ran (frame from the study film). Each pass takes the optical power ledger from the non-sequential trace (watts of light absorbed by each part), applies those watts as heat loads, solves the whole bar's thermal model, and sets each LED's light output from its solved junction temperature, then repeats. The hot-roof case converged in two passes; the energy ledger closes to 4e-14. Right: the module section coloured by its solved temperatures (70-90 C scale) and the absorbed light applied as heat. Frame from the study film; Paraxial non-sequential engine, Paraxial FEA solver.

Where it is tight

Real parts vary. In 100 simulated builds with assumed tolerances, the module loses a median 3.1% of its useful light and 14.8% in the worst build, mostly from the mirror's position and tilt. The lowest-power setting (blue 0.375 A) has almost no light to spare, so most builds would fall short. Mounting the lens so that less heat reaches it allows blue to run at 0.45 A, which leaves 16.7% to spare, more than any build lost, for 62 W. The next chapter, 'A better version', runs it through every check.

REAL PARTS VARY: 100 SIMULATED BUILDS OF THE MODULE — 100 modelled builds · 1 M rays each · assumed tolerances

Each dot is one build with random LED placement, LED output, mirror position, tilt and reflectivity. ✕ = loses more light than that setting can spare.



Red at 0.5 A has 11.5% to spare: 8 of 100 builds lose more. Tolerances are assumed (not Federal Signal data): a sensitivity check, not a production yield.

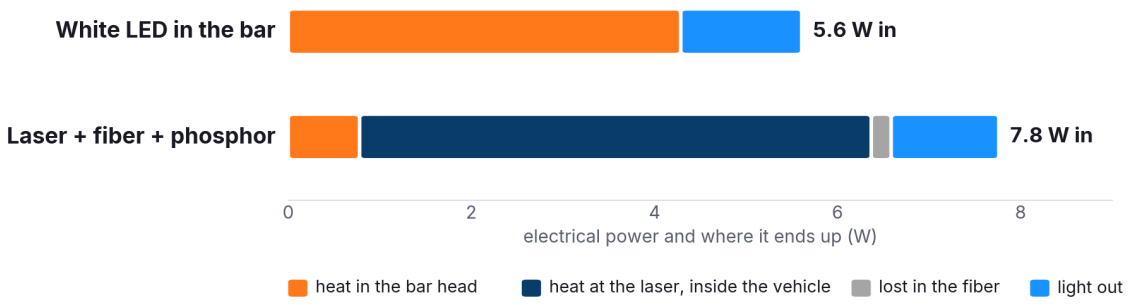
100 modelled builds of the C1 module, each with independent random LED placement (+/-0.1 mm), LED output (+/-10%), optic position (+/-0.2 mm) and tilt (+/-1 deg), and reflectivity (+/-0.02), traced at 1 M rays each. A build 'falls short' when it loses more useful light than the operating point can spare above the 110% requirement in the hot-roof case. The tolerances are assumed, so this is a sensitivity check, not a production yield.

The white-light question

White light can come from a white LED in the bar, or from a laser in the vehicle that sends blue light along a fiber to a phosphor tip in the bar. At the same useful light on the hot roof, the remote version cuts the heat in the bar head from 4.3 W to 0.8 W, but the system draws 7.8 W instead of 5.6 W, and most of that becomes heat at the laser. Its colour is right only when the phosphor absorbs about 88% of the laser light; the 95% starting value misses the white target by du'v' 0.042 against a 0.01 tolerance.

THE WHITE-LIGHT QUESTION: MOVE THE LIGHT SOURCE OFF THE BAR? two-stage converter trace · FEA heat

A laser in the vehicle sends blue light down a fiber to a phosphor tip in the bar, which turns it white. Both heads give 300 useful lm on the hot roof.



- ✓ The bar head runs cooler: 0.8 W of heat instead of 4.3 W.
- ✗ The system uses more power: 7.8 W instead of 5.6 W, most of it heat at the laser.
- ! The colour is right only if the phosphor absorbs 88% of the laser light; the starting value (95%) gives the wrong white.

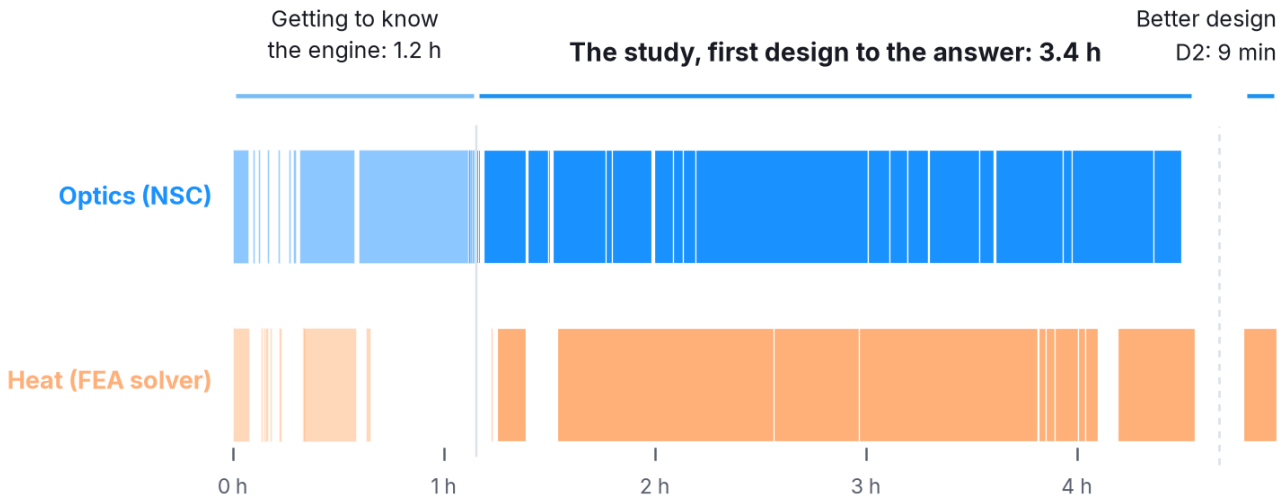
Laser safety needs a qualified review; it is flagged here, not classified.

White-light heads matched to 300 useful lm in the hot-roof case: a white LED head in the bar vs a 450 nm laser in the vehicle feeding a phosphor converter in the bar through 1 m of fiber. The laser module's location and mounting are assumptions (A16). Simulated: optics Paraxial non-sequential engine (two-stage converter trace), heat Paraxial FEA solver.

What the simulation did

How many designs it tried, and how fast. The AI agent generated 177 module designs in three families (reflector, lens, reflector + lens): 117 on a screening grid, then 60 refining the leaders. 3 failed the geometry check. The other 174 were each traced with 1 million rays from the real LED die size and scored on useful light and the 35 required directions. They ran one after another in 17 min 44 s, 6.1 s per design on average (5.4 to 9.9 s). The three finalists were then qualified with 25 traces of 2 million rays per colour, 11 s per trace on average.

What it took. An AI agent did the design and simulation work in the Paraxial API; people set the brief and approved three one-click logins. From a standing start it took 4.6 hours of simulation working time: 1.2 hours getting to know the engine (learning the API, textbook reference checks and size tests), then 3.4 hours for the study from the first design screened to the answer, with the NSC ray traces and the FEA heat solves running side by side. In all, 1,327 NSC ray traces (1.76 billion rays) and 925 heat solves on Paraxial's FEA solver. Re-running every check for the better design, D2, took 9 minutes on the FEA solver. Working hours run from the first engine call to the last, with pauses over 10 minutes removed, from the API worker's logs; writing this report and making the figures and film are not included.



Each block is one engine run. Getting to know the engine: learning the API, reference checks and size tests.

Working hours: pauses over 10 minutes with nothing running are taken out. Report and film work is not included.

In plain terms: what the design and simulation work took, as it ran. Each block is one engine run: NSC ray traces on top, FEA heat solves below, running side by side. From a standing start: 1.2 h getting to know the engine (learning the API, textbook reference checks and size tests, including batch jobs that stalled), then 3.4 h for the study from the first design screened to the answer; re-running every check for the better design, D2, took 9 min on the FEA solver. In all, 1,327 NSC ray traces (1.76 billion rays) and 925 heat solves. Working hours run from the first engine call to the last, with pauses over 10 minutes removed, from the API worker's logs; report, figure and film work is not included.

WHAT THE SIMULATION ACTUALLY DID

Paraxial optics + FEA

Light and heat were solved together: each depends on the other.

1 Build the designs

The agent generated 177 module designs in three families; 3 failed the geometry check; 174 were traced, 1 M rays each, in 18 minutes.

2 Trace the light

Millions of rays from the real LED chip size through mirror and lens: 50 M per colour for each finalist, 140-180 M for the whole bar.

3 Solve the heat

A thermal model of the whole bar: 72 LEDs, drivers, electronics, sun, roof, air. Five weather cases; 274 solved states.

4 Couple them

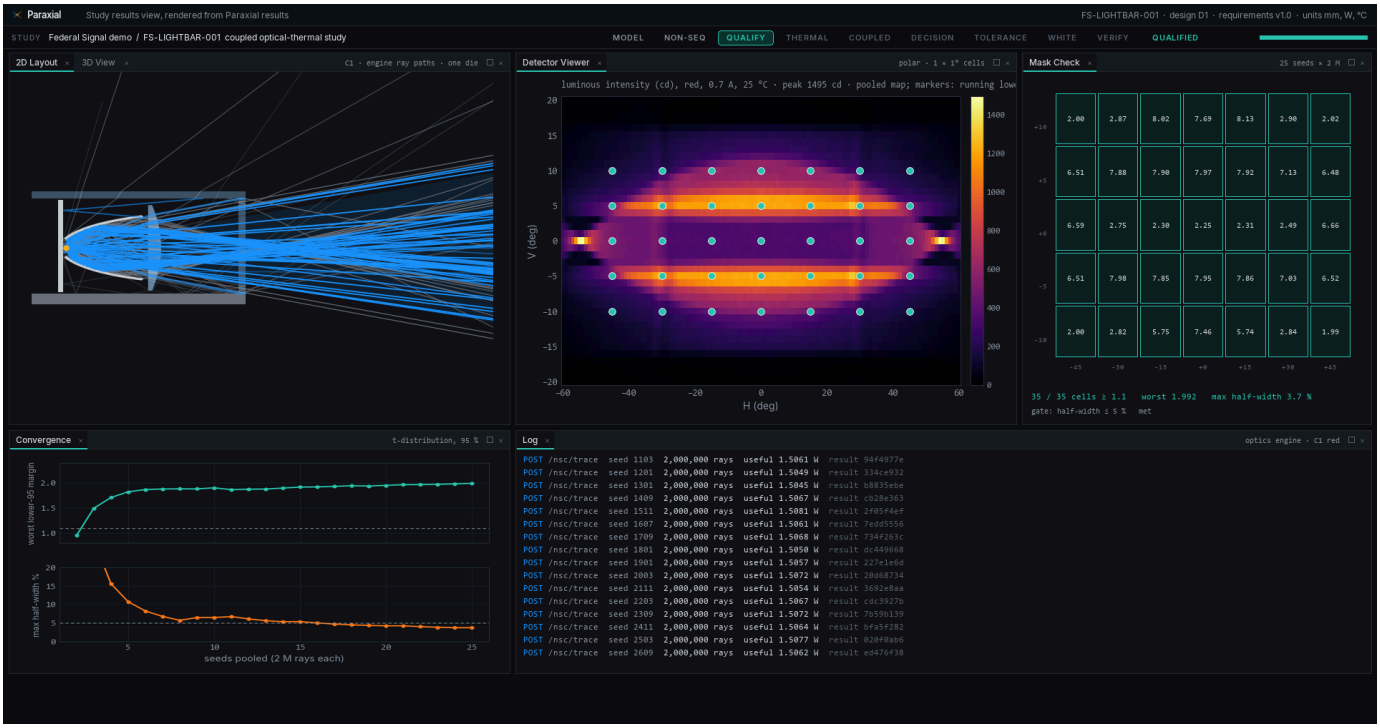
Hot LEDs give less light; light absorbed by the lens and mirror heats them. Repeated until light and heat agree.

5 Check and stress-test

35 directions per module and 120 around the bar, with a statistical margin. 100 simulated builds; cooling assumptions halved and doubled.

Optics: Paraxial non-sequential engine. Heat: Paraxial FEA solver.

How the study was run. Every number in this report traces to a saved run file listed in evidence.json.



Qualification of the selected optic as it ran (frame from the study film). Each 2 M-ray trace adds one seed: the 35 mask cells are re-judged on the running lower 95 % bound (t-distribution over seeds) and turn green once they clear 1.1 x target; the convergence plots show the worst cell's bound and the largest cell half-width settling below the 5 % ray-noise gate. Log: every trace with its seed, engine time, useful flux and result id. C1, red, 0.7 A, 25 C; Paraxial non-sequential engine.

How to read the engineering sections

- **Candela (cd):** how bright a light looks from one direction. Targets here are synthetic: red 150 cd in the centre and 75 cd at the edges of each module's view.

- **Mask point, cell or required direction:** one of the directions where brightness is checked: 35 per module, 120 around the whole bar.
- **Margin:** brightness divided by its target. The requirement is 1.1 (110% of target); a margin of 1.24 means 124% of target.
- **Lower 95% bound:** the simulation counts light with random rays, so each brightness carries a small statistical uncertainty. Every check uses the pessimistic end.
- **Useful light (useful flux):** light that leaves within 45 degrees either side and 10 degrees above or below level, the box drivers are in.
- **H and V:** horizontal and vertical angle from straight ahead of a module. H -45 to 45, V -10 to 10 is the required box.
- **Junction temperature (Tj):** the temperature of the LED chip itself; pulse peak is its hottest moment during a 100 ms flash.
- **T1 to T5:** the weather cases: -40 C cold, 25 C room, 65 C hot shade, 85 C roof in 1000 W/m2 sun, and the same roof with forced cooling.
- **A1, B1, C1:** the finalists of the reflector-only, lens-only and reflector + lens families. Baseline: bare LEDs.
- **du'v':** the distance between two colours on the standard colour chart; below 0.01 counts as the same white.

A better version: what the first answer taught us

D1 answers the question. It is also the lowest-power design that passes, so it has very little to spare. Because one model holds the light, the heat and the build-to-build variation together, the study could find where D1 is fragile, change one thing, and run every check D1 passed again. This chapter is that second pass.

What the first design taught us

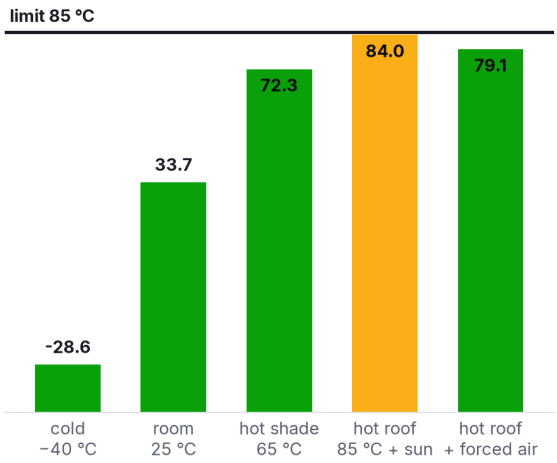
D1 meets every requirement, and the same results show its two tight spots. On a hot roof the plastic lens runs at 84.0 C against its 85 C limit. And at its lowest-power setting, blue gives only 0.5% more light than required. Real parts vary: in 100 simulated builds with assumed tolerances the module loses a median 3.1% of its useful light, up to 14.8%, mostly from the mirror's position and tilt. So 80 of the 100 builds would fall short in blue (8 in red).

WHAT THE FIRST ANSWER TAUGHT US: TWO TIGHT SPOTS — D1 · coupled T1–T5 · 100 modelled builds

Design D1 (standard lens mount, red 0.5 A, blue 0.375 A) meets every requirement. The same results show exactly where it is fragile.

1. The plastic lens on a hot roof

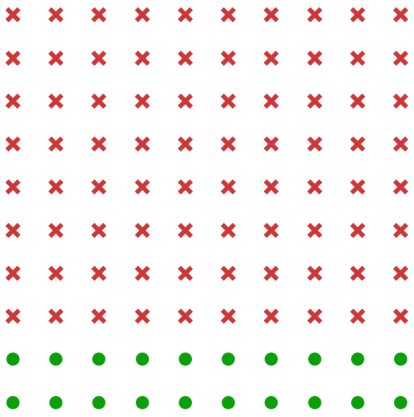
Hottest lens temperature in each weather case (°C), both colours



1.0 °C to spare on the hot roof

2. Blue light to spare: 0.5%

100 simulated builds; × = falls short at blue 0.375 A



80 of 100 builds fall short (red at 0.5 A: 8 of 100)

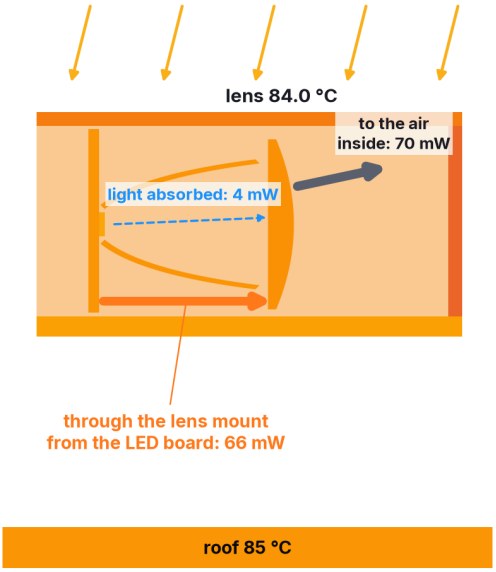
In plain terms: Where the first design is fragile: the lens is close to its limit on a hot roof, and blue has almost no light to spare. D1, the first answer, worst of both colours. Left: the hottest plastic-lens temperature in each of the five weather cases against its 85 C limit. Right: 100 simulated builds of the module with independent random LED placement, LED output, optic position and tilt, and reflectivity (assumed tolerances), each traced at 1 M rays; a build falls short when it loses more useful light than blue at its selected current can spare above the 110% requirement in the hot-roof case. Simulated: optics Paraxial non-sequential engine, heat Paraxial FEA solver.

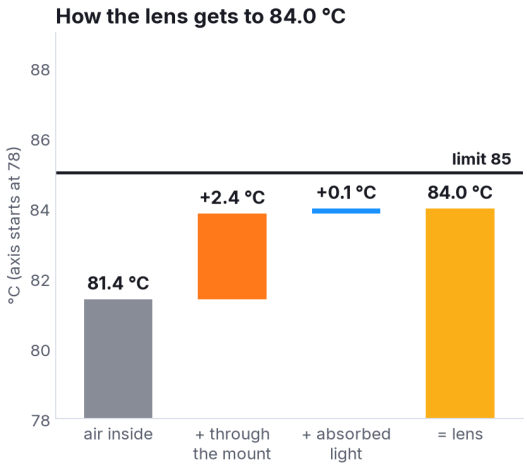
Why it was tight

On the hot roof the air inside the bar is already at 81.4 C, and the lens sits 2.6 C above it. The heat balance of the hottest lens shows where that comes from: 66 mW arrive through the lens mount from the LED board, and only 4 mW from the light the lens absorbs. So 94% of the lens's heat comes in through its mount. That is the path to cut.

WHY IT WAS TIGHT: THE LENS IS HEATED MOSTLY THROUGH ITS MOUNT FEA · solved node temperatures · lens heat balance

Hot roof (85 °C roof, full sun), blue flashing at 0.375 A, the hottest lens in the bar. Flows from the solved temperatures.





94% of the lens's heat comes through its mount.

The lens can't be cooler than the air around it (81.4 °C). The +2.4 °C via the mount is what a change can remove.

In plain terms: Where the lens's heat comes from: almost all of it arrives through its mount from the LED board. Heat balance of the hottest lens in the bar on the hot roof (D1, blue). The lens node in the thermal model has three connections: the lens mount to its module's LED board (0.05 W/K, assumption A19), convection to the air inside the bar, and the light it absorbs from the trace's power ledger. Arrow widths are to scale; every flow is computed from the solved node temperatures and the model's own conductances, and the balance closes to better than 1e-14 W. The axis on the right starts at 78 C. Simulated, Paraxial FEA solver.

The change, and what it costs

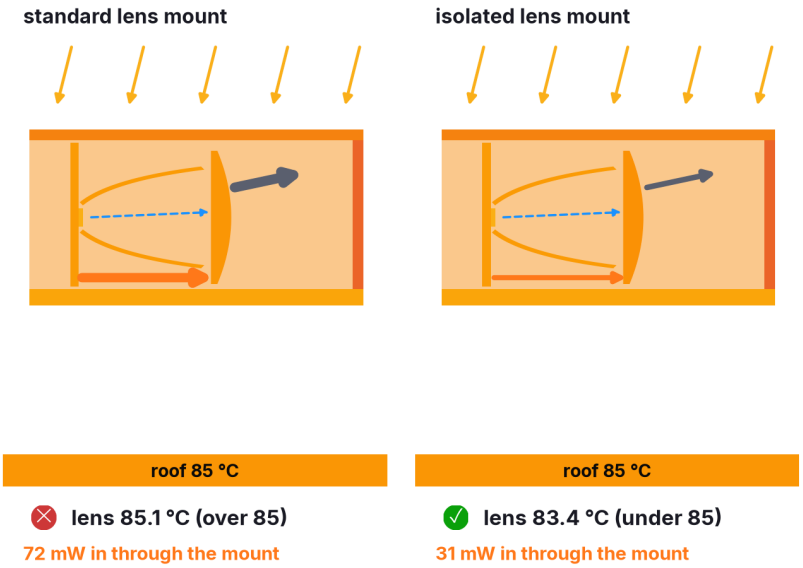
We isolated the lens mount: in the model, the heat path from the LED board into each lens goes from 0.05 to 0.01 W/K. Physically that means holding the lens so that less heat crosses from the LED board into it, for example on a few small low-conductance contact points instead of a full seat. It is an assumption (A19); a real mount design would set the value. At the same blue current of 0.45 A, the standard mount puts the lens at 85.1 C, over its limit; the isolated mount keeps it at 83.4 C. That is what lets the LEDs run harder: blue goes from 0.375 A to 0.45 A and red from 0.5 A to 0.55 A.

The cost is power: the bar's average goes from 52 W to 62 W and its peak from 99 W to 118 W, still well inside the 100 W and 200 W budgets. Red's higher current costs nothing at the bar level, because the bar flashes one colour at a time and blue draws more.

THE CHANGE: ISOLATE THE LENS MOUNT, THEN DRIVE THE LEDS HARDER

FEA · T4 · A19 0.05 → 0.01 W/K

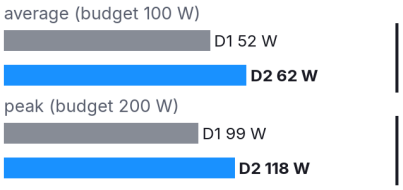
One modelled change: LED board → lens heat path 0.05 → 0.01 W/K (an assumption, A19). Left: both mounts at blue 0.45 A, hot roof.



What changes from D1 to D2

	D1	D2
Lens mount	standard	**isolated (assumed)**
Red current	0.5 A	**0.55 A**
Blue current	0.375 A	**0.45 A**
Lens, hot roof	84.0 °C	**83.4 °C**
Light to spare, red	11.5%	**19.3%**
Light to spare, blue	0.5%	**16.7%**

What it costs: power (whole bar)



In plain terms: With the isolated mount, the lens stays under its limit even at the higher blue current. The same blue current (0.45 A) on the hot roof with the standard lens mount (0.05 W/K) and the isolated lens mount (0.01 W/K, assumption A19). In the model the mount is one number: the conductance from each lens to its LED board. Physically it means holding the lens so that less heat crosses from the LED board into it, for example on small low-conductance contact points instead of a full seat; a real mount design would set the value. Power is the whole bar's electrical input at the warning duty; the bar runs one colour at a time, so a design's power is that of its hungrier colour. Simulated, Paraxial FEA solver.

The proof

D2 went through every check D1 passed, with the same rules: all five weather cases, the 100 ms flashes, the full bar at 120 directions, the power budget and the 100 simulated builds. It passes all of them. Its dimmest required direction is 136% of target in red and 132% in blue (D1: 124% and 110.6%); the dimmest of the bar's 120 directions is 220%; the hottest LED chip is 90.5 C (limit 105 C) and the lens 83.4 C. Judged against D2's light to spare, none of the 100 simulated builds falls short in either colour.

The builds were not re-traced. The mount changes how heat flows, not where the light goes, so the same traced builds are judged again against D2's own operating point.

THE PROOF: D2 PASSES EVERY CHECK D1 PASSED, WITH ROOM TO SPARE

same gates as D1 · optics + FEA

Worst case over all five weather cases and both colours. D2: isolated lens mount, red 0.55 A, blue 0.45 A. Same rules, same requirements.

	D1 (first answer)	D2 (recommended)	requirement
Dimmest required direction, red	✓ 124%	✓ **136%**	≥ 110%
Dimmest required direction, blue	! 110.6%	✓ **132%**	≥ 110%
Dimmest of 120 directions around the bar	✓ 185%	✓ **220%**	≥ 110%
Hottest LED chip	✓ 88.5 °C	✓ **90.5 °C**	≤ 105 °C
Hottest plastic part (the lens)	! 84.0 °C	! **83.4 °C**	≤ 85 °C
Average power, whole bar	✓ 52 W	✓ **62 W**	≤ 100 W
Peak power, whole bar	✓ 99 W	✓ **118 W**	≤ 200 W
Simulated builds that fall short, red	! 8 of 100	✓ **0 of 100**	none required
Simulated builds that fall short, blue	✗ 80 of 100	✓ **0 of 100**	none required

Builds are re-judged against each design's own light headroom; tolerances are assumed, so this is a sensitivity check, not a production yield.

In plain terms: The robust design passes every check the first design passed, with more to spare on light. D1 and D2 against every requirement D1 was qualified by, worst case over the five weather cases and both colours: module directions on the lower 95% bound of the pulse-on intensity at the pulse-peak junction temperature, the full 12-module bar at 120 directions (70 red and 90 blue traces of 2 M rays, normalised to 0.7 A and 25 C and scaled by each case's weakest-module output), junction and polymer temperatures, bar power, and the 100 modelled builds. Simulated: optics Paraxial non-sequential engine, heat Paraxial FEA solver.

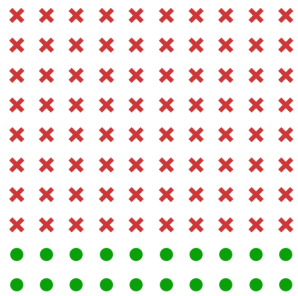
THE SAME 100 SIMULATED BUILDS, JUDGED AGAIN

m1 v4 · 100 builds · 1 M rays each

The mount changes how heat flows, not where the light goes, so the traced builds are reused and re-judged against D2's light to spare. ✕ = falls short.

D1: blue at 0.375 A

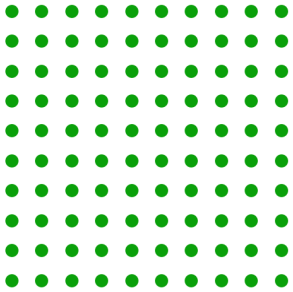
standard mount, 52 W; 0.5% light to spare



✗ **80 of 100 fall short**

D2: blue at 0.45 A

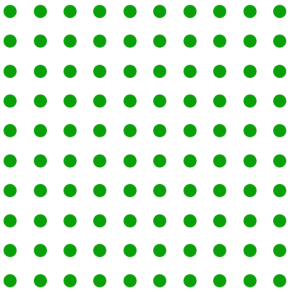
isolated mount, 62 W; 16.7% light to spare



✓ **0 of 100 fall short**

D2: red at 0.55 A

isolated mount, 62 W; 19.3% light to spare



✓ **0 of 100 fall short**

Worst build loses 14.8% of its useful light (median 3.1%), mostly from mirror position and tilt. D1 red at 0.5 A: 8 of 100 short. Tolerances assumed.

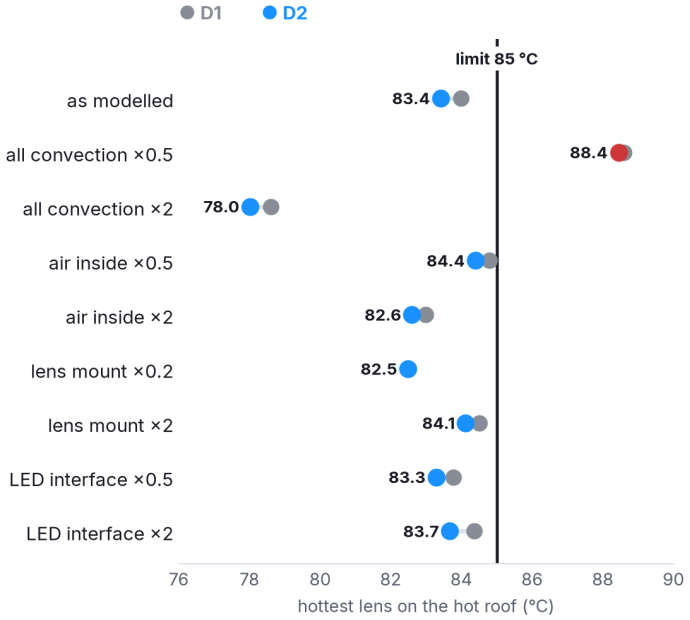
In plain terms: With more light to spare, none of the 100 simulated builds falls short. The 100 modelled builds of the C1 module (the same traced builds as figure A8), each judged against the light headroom of the operating point in the hot-roof case: headroom = 1 - 1.1 / worst margin. Reusing the builds is valid because the lens mount changes the heat path, not the optical geometry; the headroom is recomputed at D2's own operating state. Tolerances are assumed, so this is a sensitivity check, not a production yield. Simulated, Paraxial non-sequential engine.

What it is most sensitive to

The lens is still the part closest to its limit, with 1.6 C to spare. Against every uncertain cooling assumption the study varied, D2's lens stays under 85 C but one: if the bar loses heat to the outside air only half as well as assumed, the air inside the bar reaches 86.4 C, itself above the lens limit, and no lens mount could fix that. The convection values are demonstration assumptions, so the cooling on a real roof is what this result is most sensitive to. Like every other assumption here, it is an input to the same model: change it and every check runs again.

WHAT IT IS MOST SENSITIVE TO: THE AIR INSIDE THE BAR ON A HOT ROOF FEA · T4 · boundary sensitivity

Hottest lens on the hot roof when each uncertain cooling assumption is halved or doubled (worst of both colours). Convection values are assumptions.



What it shows

- Against every assumption except weaker convection, D2's lens stays under 85 °C.
- With half the assumed convection, the air inside the bar reaches 86.4 °C, itself over the lens limit, so no lens mount can fix it.
- So the cooling on a real roof is the assumption this result is most sensitive to.

Every assumption is an input

The convection, the lens mount and the LED data are all inputs to the same model. Change any one and it re-runs every check in this study: light, heat, power and the 100 builds.

In plain terms: The design holds against every cooling assumption except weaker convection, the assumption the result is most sensitive to. Boundary sensitivity on the hot roof (85 C roof, 1000 W/m2 sun, 65 C air): each uncertain thermal assumption halved or doubled (mount: x0.2 and x2) for D1 and D2, hottest lens of both colours. The convection coefficients are proposed demonstration values; with all of them halved the internal air itself exceeds 85 C in both designs. Simulated, Paraxial FEA solver.

What made this possible. One model carried the light, the heat and the build-to-build variation together, so the weak spot, its cause, the change and the re-check all came from the same results.

1. Engineering decision

Question. Which optical and thermal architecture meets fixed angular warning-light requirements in a 33 mm-tall roof bar, at the lowest reasonable input power and with adequate temperature margin, from -40 C to a 65 C day on an 85 C sun-loaded roof? Separately: does a fiber-fed remote-phosphor white head improve the head's thermal situation at matched useful output, and at what cost?

What we studied. A representative 1200 x 295 x 33 mm bar 25 mm above the roof: 12 modules (5 front, 5 rear, 2 ends) of six 0.8 mm red/blue/white LED packages each. Each module was given three optical architectures in the same 180 x 45 x 27 mm envelope (a shallow compound reflector, a cylindrical refractor and a hybrid of the two), compared with bare LEDs. Every architecture was traced with finite emitting dies (finalists: 50 million rays per colour), and coupled to a thermal network of the whole bar with the LEDs, drivers, controller, processor, roof, sun and 100 ms / 100 ms flash pulses.

Fixed requirement (study_spec v1.0, proposed demonstration values)	Value
Light (module)	every mask point: lower 95% bound of pulse-on intensity >= 1.1 x target; red 150/75 cd, blue 60/30 cd (central/outer), H -45..45, V -10..10 deg
Light (bar)	every 15 deg in H, V -10..10 deg: >= 1.1 x 100 cd red, 40 cd blue
Useful light	>= 30% of each module's launched radiant power inside H +/-45, V +/-10 deg
Temperature	LED junction <= 105 C (pulse peak), polymer optics <= 85 C, phosphor <= 120 C
Power	<= 15 W peak per module, <= 200 W peak and <= 100 W average per bar at the warning duty (6 W controls included)
Cases	T1 cold -40 C; T2 room 25 C; T3 hot shade 65 C; T4 hot roof 85 C + 1000 W/m2 sun; T5 T4 with forced cooling (h = 50)

Result: C1 hybrid reflector + refractor (standard lens mount) meets every fixed requirement in both colours, in all five thermal cases, at red 0.500 A and blue 0.375 A per die. Worst-cell margins (lower 95% bound / target, worst case over the five cases, pulse-on at the pulse-peak junction temperature) are 1.24 red and 1.11 blue. The hottest pulse-peak junction is 88.5 C (limit 105 C) and the hottest polymer part 84.0 C (limit 85 C). The bar draws at most 99 W peak and 52 W average at the warning duty (budgets 200 W and 100 W).

Worst operating condition. The lowest angular margin is 1.11 (blue, hot roof and sun, cell H -45, V -10); the hottest polymer part reaches 84.0 C (blue, hot roof and sun) and the hottest pulse-peak junction 88.5 C (blue, hot roof and sun). **Strongest remaining uncertainty.** The polymer lens temperature in the hot-roof case (1.0 K below 85 C). It is most sensitive to every convection coefficient (outside and inside; proposed demonstration values): x0.5 raises it +4.6 K (blue, to 88.6 C, past the limit). That is the assumption this result is most sensitive to.

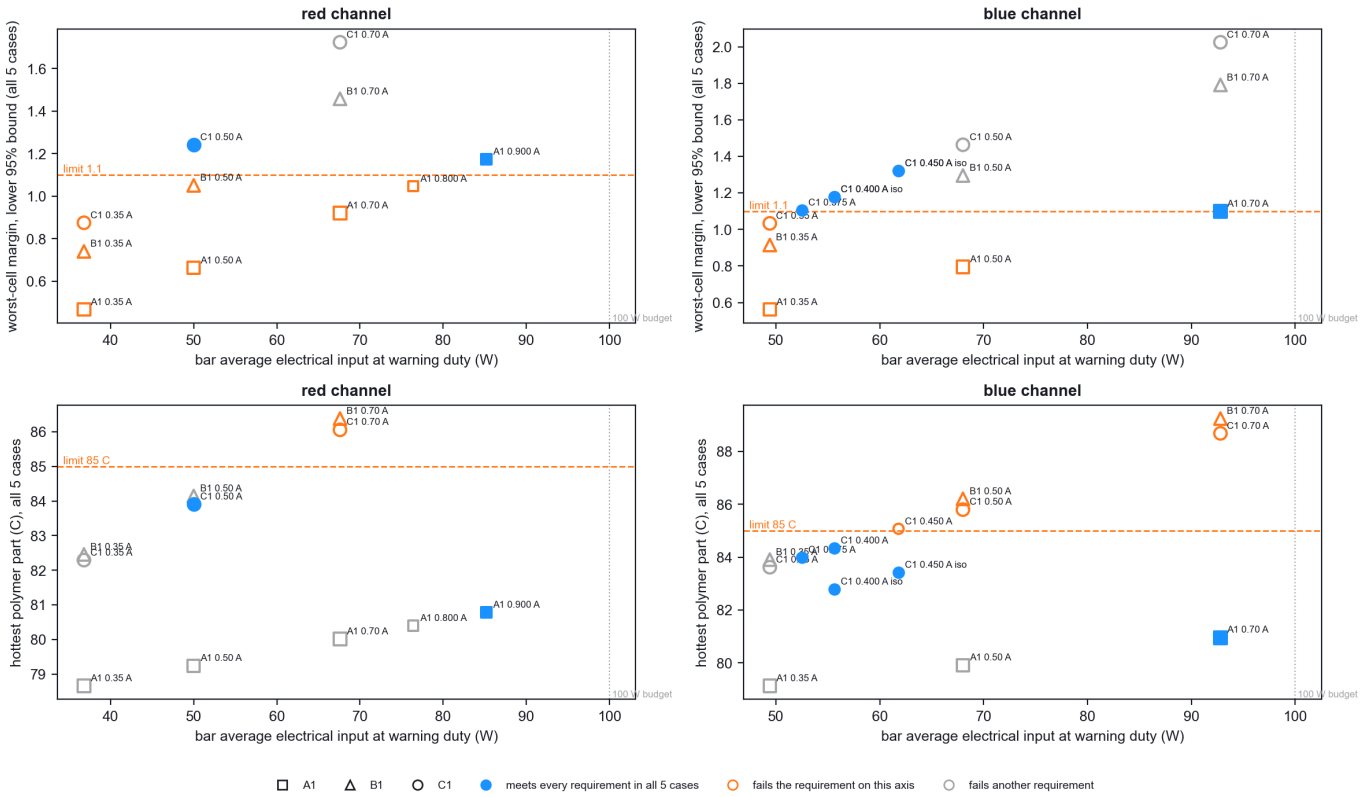
Operating margin. The selected currents are the lowest that pass. Blue at 0.400 A also passes, with margin 1.18 instead of 1.11 and the hottest polymer part at 84.3 C, for 56 W instead of 52 W bar average. That is the better operating point if the thin margin at the selected current is a concern.

Robustness (modelled builds, not a yield). Under the assumed tolerances the module loses a median 3.1% of its useful light (worst 14.8%), mostly from the reflector's position and tilt. C1 red 0.500 A has 11.5% light headroom and 8% of modelled builds lose more; C1 blue 0.375 A has 0.5% light headroom and 80% of modelled builds lose more; C1 blue 0.400 A has 6.6% light headroom and 23% of modelled builds lose more. With the isolated lens mount, blue at 0.450 A passes every case with margin 1.32, which is 16.7% headroom, more than any modelled build lost (14.8%), for 62 W average. That combination, with red raised to 0.55 A, is the robust design D2 (section 7).

Design	Colour	Lowest feasible current	Worst margin	Junction peak (C)	Polymer max (C)	Bar avg / peak	Status or binding (by current)
A1 compound reflector	red	0.900 A	1.17	96.1	80.8	85 / 164 W	meets all
A1 compound reflector	blue	0.700 A	1.10	96.9	81.0	93 / 180 W	meets all
B1 cylindrical refractor	red	none of those evaluated	1.46	85.9	82.5	-	0.350 A: mask_margin, useful_flux_fraction; 0.500 A: mask_margin, useful_flux_fraction; 0.700 A: polymer, useful_flux_fraction
B1 cylindrical refractor	blue	none of those evaluated	1.79	88.3	83.9	-	0.350 A: mask_margin, useful_flux_fraction; 0.500 A: polymer, useful_flux_fraction; 0.700 A: polymer, useful_flux_fraction
C1 hybrid reflector + refractor (standard lens mount)	red	0.500 A	1.24	88.5	83.9	50 / 94 W	meets all
C1 hybrid reflector + refractor (standard lens mount)	blue	0.375 A	1.11	88.5	84.0	52 / 99 W	meets all
C1 hybrid with an isolated lens mount (0.01 W/K)	blue	0.400 A	1.18	89.2	82.8	56 / 105 W	meets all

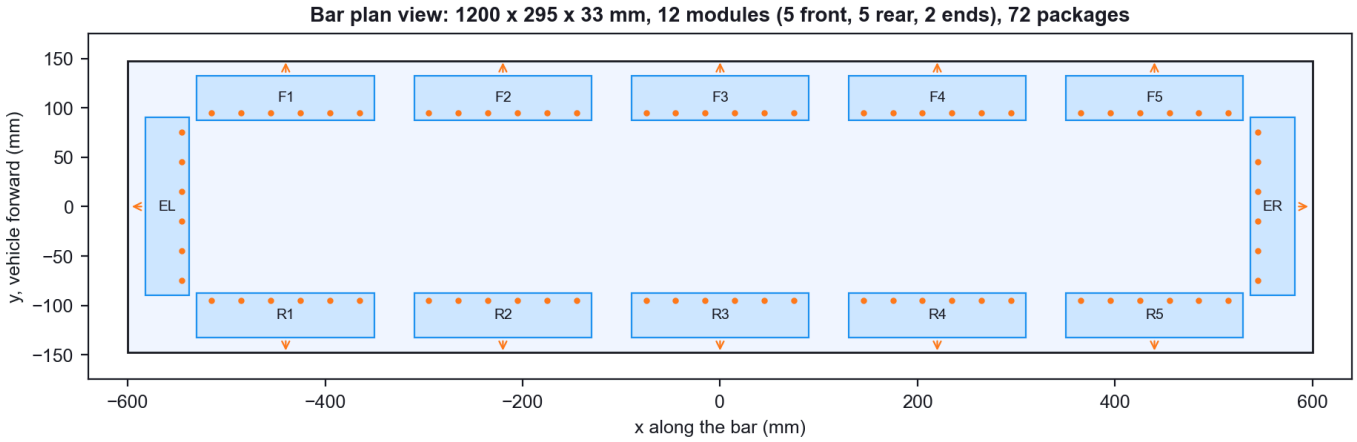
All five thermal cases at the 100 ms / 100 ms warning duty. Currents evaluated: 0.35, 0.50, 0.70 A per die for every candidate, plus option points (0.375-0.45 A blue for C1, 0.80-0.90 A red for A1, isolated lens mount). Polymer = lens (B, C), outer lens and top cover.

Trade-off: angular margin and polymer temperature against input power (option points include intermediate currents and an isolated lens mount)

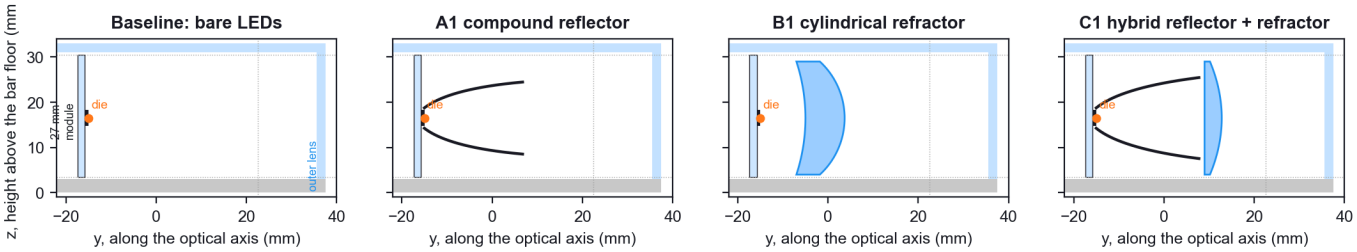


In plain terms: Each point is one design at one current: more margin for less power is better, and filled points pass everything. Candidate trade-off. Each point is one candidate and drive current evaluated in all five thermal cases (cold, room, hot shade, hot roof + sun, improved cooling) at the 100 ms / 100 ms warning duty: the worst-cell margin is the lowest lower-95%% bound / target over all cases (pulse-on output at the pulse-peak junction temperature), the polymer temperature the hottest polymer part (lens for B and C, outer lens and top cover for all). Filled blue = meets every fixed requirement. Optics: Paraxial non-sequential engine, 50 M rays per finalist; thermal: Paraxial FEA solver coupled network. 'iso' = optic mount conductance 0.01 W/K instead of 0.05 W/K (assumption A19). Synthetic mask; not SAE.

2. Model and assumptions



In plain terms: The bar seen from above, with its 12 modules and 72 LEDs. Plan view of the 12-module bar (bar frame: x along the bar, y vehicle forward; H = 0 is +y). Orange dots: LED packages (three dies each, one colour active); arrows: module optical axes (yaw 0 front, 180 rear, -90/+90 ends). Bar 1200 x 295 x 33 mm with 25 mm roof gap, 3 mm base and 2 mm top cover (study_spec v1.0 representative envelope; not a Federal Signal layout).



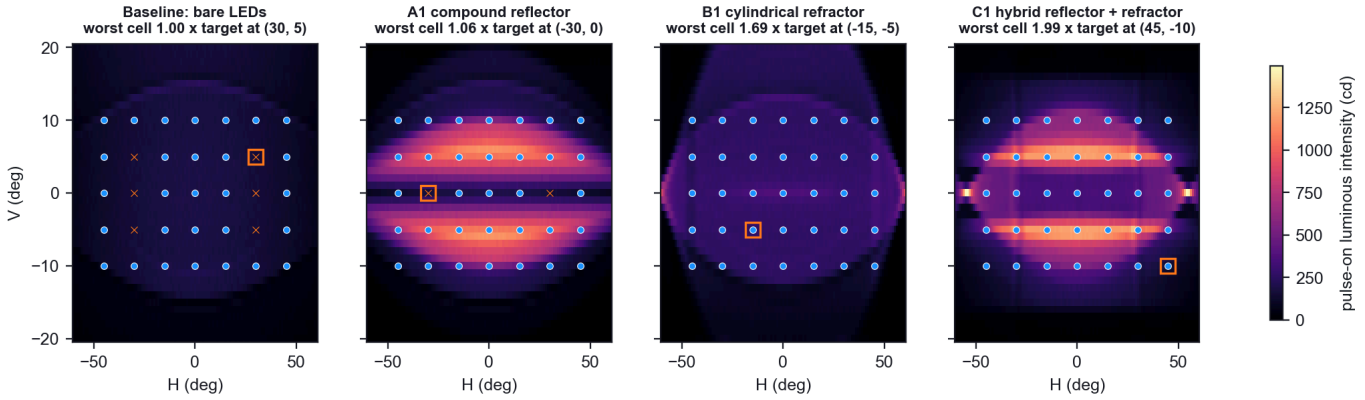
In plain terms: Side cuts through the four module designs, to scale. Module cross-sections (y-z plane at x = 90 mm) of the baseline and the three optical architectures in the same 180 x 45 x 27 mm envelope, drawn to scale from the exact scene geometry traced (designs BASE, A1, B1, C1; study FS-LIGHTBAR-001, requirements v1.0, design D1). Dotted lines: module envelope. Grey: bar floor; blue: 2 mm polymer outer lens and top cover. Extruded along x for 180 mm; six packages at x = -75..75 mm. Geometry: study assumptions A01-A07 (synthetic, not a Federal Signal design).

Input	Value	Provenance
LED dies	0.8 x 0.8 mm, Lambertian; modelled as equal-area 0.903 mm discs (rectangular sources unavailable in this build); red 625 nm and blue 470 nm, 20 nm FWHM; 2.2 / 3.1 V; 30% / 35% efficient at 25 C, -0.2%/K	study_spec (synthetic)
Photometry	CIE 018:2019 1 nm V(lambda) and CIE 1931 2 deg tables, publisher checksums verified	CIE datasets
Optics	polymer n 1.49, dn/dT -1e-4/K, CTE 70 ppm/K, bulk absorption 0.001/mm; reflector 0.90 specular; 2 mm outer lens and top cover	study_spec
Thermal	aluminium base 3 mm (k 167); LED junction-board 4 K/W, board-base 2 K/W per LED; interface 0.185 K/W per module; drivers 90%; controller 2 W, processor 4 W	study_spec
Boundaries	air h 10 (top, sides) / 3 (25 mm roof gap) W/m2K, forced 50; emissivity 0.85; sun 1000 W/m2 x 0.2 absorbed; roof radiation; 4 polymer feet	study_spec + A11-A14
Waveform	100 ms on / 100 ms off, all heads synchronous, one colour; continuous drive characterised separately	study_spec
Added assumptions	20 stated assumptions (appendix B), including internal air h = 3 W/m2K and optic mount 0.05 W/K, which control the lens temperature	this study

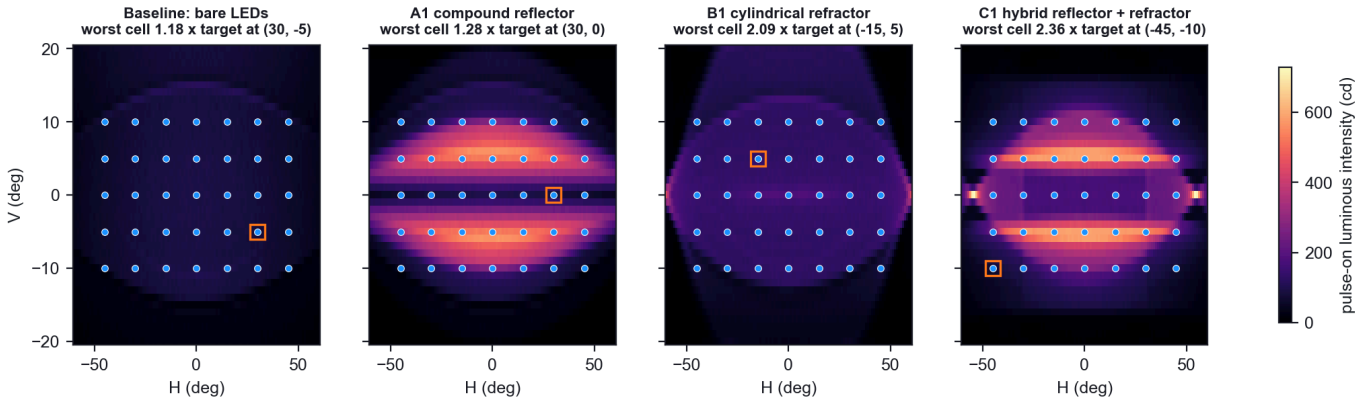
All values are proposed demonstration assumptions. Federal Signal part data, files and approved targets replace them when supplied.

Every scene, trace and thermal study behind these results is recorded with its identifier, inputs and settings, and can be supplied on request.

3. Warning-light design comparison



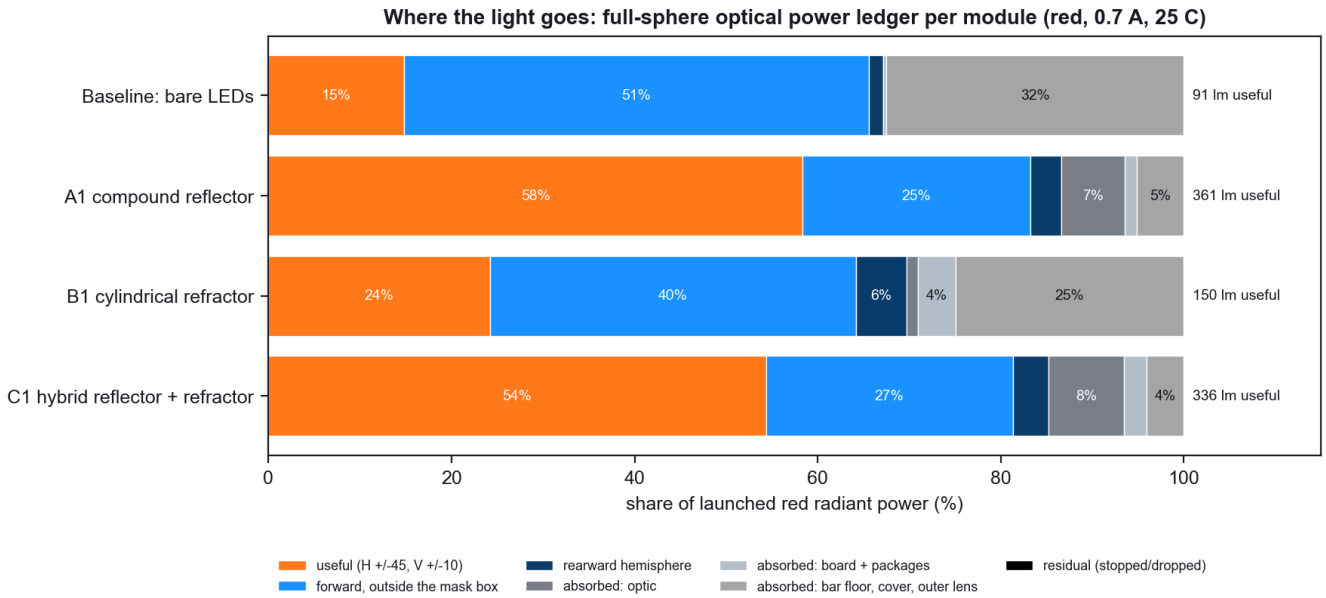
In plain terms: How bright each design looks from every direction (brighter = more light); dots are the required directions. Absolute red luminous intensity maps, same axes and colour scale, module level, 0.7 A per die at Tj = 25 C (normalisation state), 1 x 1 deg cells (exact solid angle), CIE 018:2019 1 nm V(lambda). Markers: the 35 synthetic mask points (blue = lower 95% bound >= 1.1 x target, orange x = below); orange square = worst cell. Simulated on Paraxial non-sequential engine, Simple Splitting, {"BASE": 10, "A1": 25, "B1": 25, "C1": 25} independent seeds x 2 M rays per design; scene IDs in engineering_summary.json. Finite Lambertian equal-area disc dies (A01). Synthetic mask, not SAE.



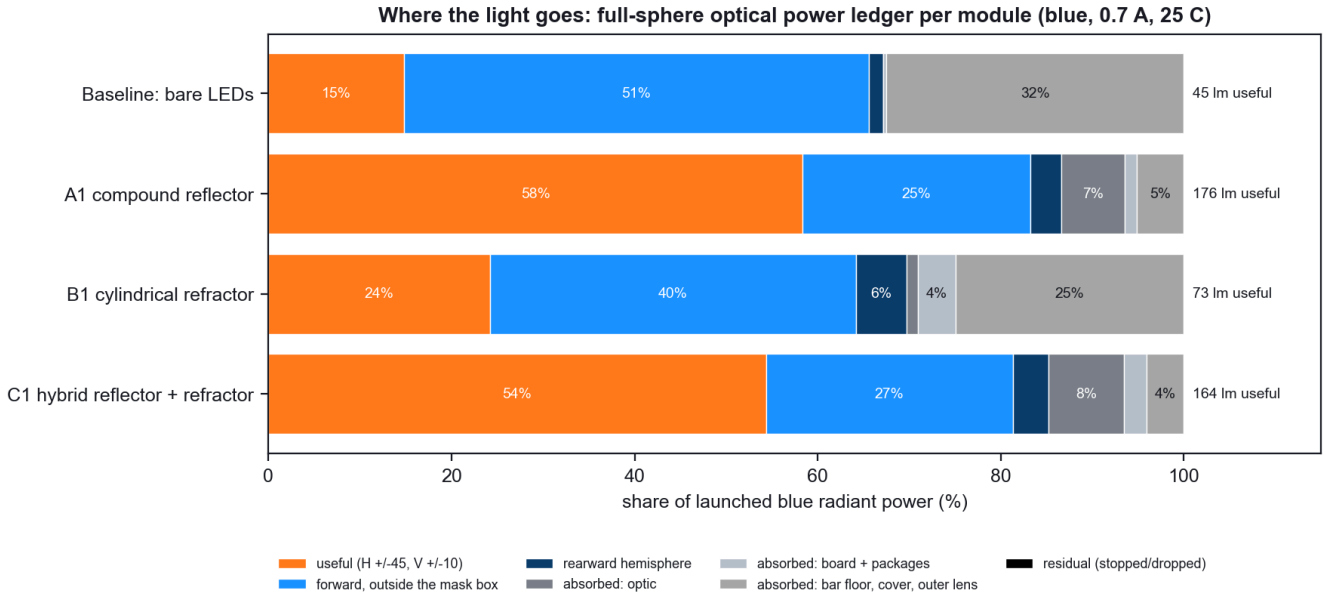
In plain terms: How bright each design looks from every direction (brighter = more light); dots are the required directions. Absolute blue luminous intensity maps, same axes and colour scale, module level, 0.7 A per die at Tj = 25 C (normalisation state), 1 x 1 deg cells (exact solid angle), CIE 018:2019 1 nm V(lambda). Markers: the 35 synthetic mask points (blue = lower 95% bound >= 1.1 x target, orange x = below); orange square = worst cell. Simulated on Paraxial non-sequential engine, Simple Splitting, {"BASE": 10, "A1": 25, "B1": 25, "C1": 25} independent seeds x 2 M rays per design; scene IDs in engineering_summary.json. Finite Lambertian equal-area disc dies (A01). Synthetic mask, not SAE.

Design	Colour	Useful light	Useful lm	Worst margin	at (H, V)	95% half-width	Rearward	Rays
Baseline (bare LEDs)	red	15%	91	1.00	(30, 5)	8.5%	1.6%	10 x 2 M
Baseline (bare LEDs)	blue	15%	45	1.18	(30, -5)	8.6%	1.6%	10 x 2 M
A1 compound reflector	red	58%	361	1.06	(-30, 0)	3.9%	3.4%	25 x 2 M
A1 compound reflector	blue	58%	176	1.28	(30, 0)	4.4%	3.4%	25 x 2 M
B1 cylindrical refractor	red	24%	150	1.69	(-15, -5)	3.9%	5.5%	25 x 2 M
B1 cylindrical refractor	blue	24%	73	2.09	(-15, 5)	3.3%	5.5%	25 x 2 M
C1 hybrid reflector + refractor	red	54%	336	1.99	(45, -10)	3.7%	3.9%	25 x 2 M
C1 hybrid reflector + refractor	blue	54%	164	2.36	(-45, -10)	3.6%	3.9%	25 x 2 M

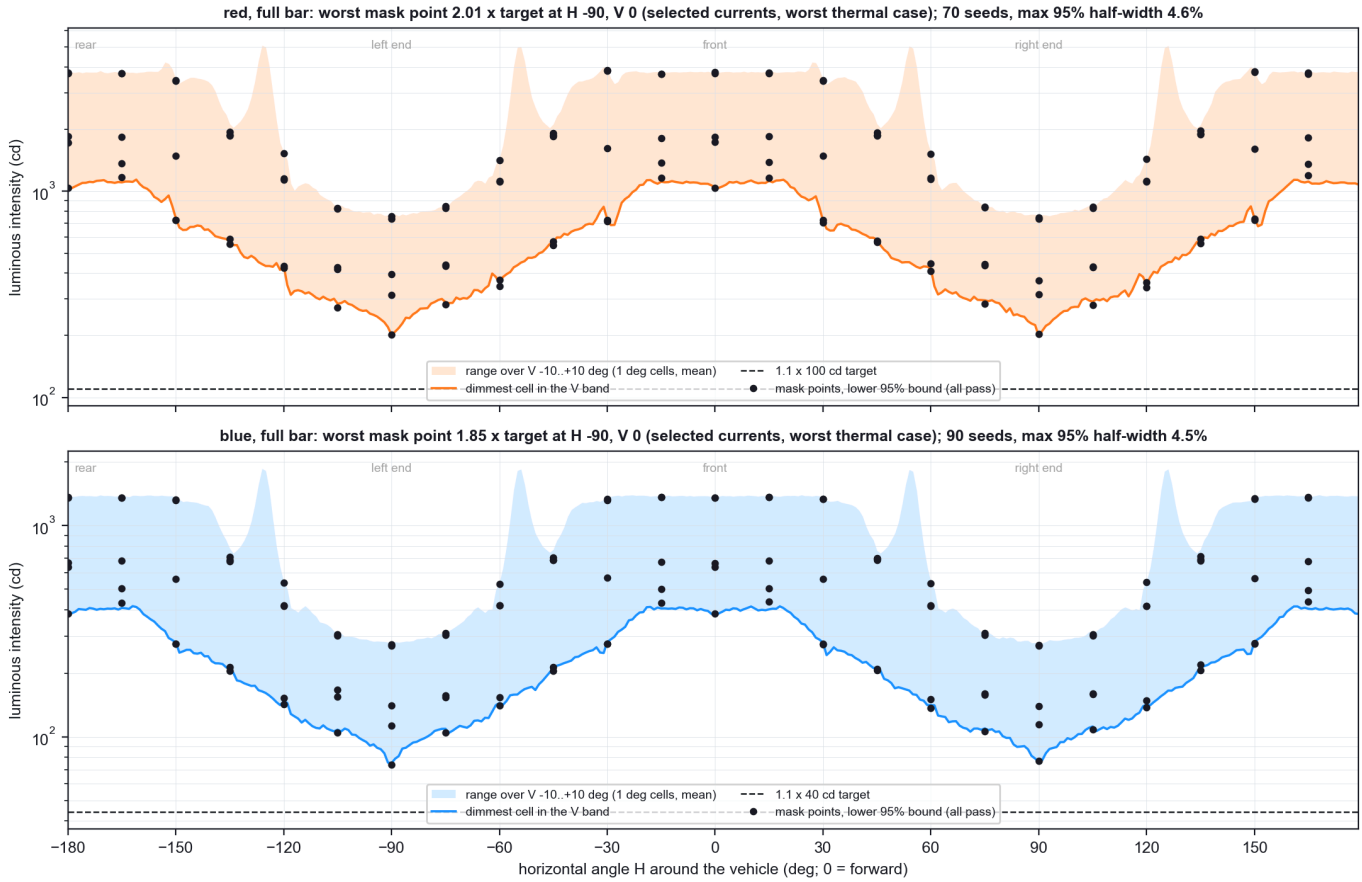
Module level at 0.7 A per die and Tj = 25 C (normalisation state). Worst margin = lowest lower-95% bound / target over the 35 mask points. Thermal derating is applied in section 1 and 4.



In plain terms: Where every watt of light from each design ends up. Optical power ledger per module, red channel at 0.7 A and Tj 25 C: every launched watt is assigned to the mask box (useful, H +/-45 deg, V +/-10 deg), forward light outside it, rearward escape (full sphere detector), absorption per part (bulk absorption 0.001/mm in polymers, 0.90 reflector), or the tracked residual (rays stopped at the trace limits). Closure error < 1e-11 %. Absolute useful flux in lumens with CIE 018:2019 V(lambda). Simulated, Paraxial non-sequential engine, Simple Splitting, 25 seeds x 2 M rays for A1, B1, C1 (10 for the baseline).



In plain terms: Where every watt of light from each design ends up. Optical power ledger per module, blue channel at 0.7 A and Tj 25 C: every launched watt is assigned to the mask box (useful, H +/-45 deg, V +/-10 deg), forward light outside it, rearward escape (full sphere detector), absorption per part (bulk absorption 0.001/mm in polymers, 0.90 reflector), or the tracked residual (rays stopped at the trace limits). Closure error < 1e-11 %. Absolute useful flux in lumens with CIE 018:2019 V(lambda). Simulated, Paraxial non-sequential engine, Simple Splitting, 25 seeds x 2 M rays for A1, B1, C1 (10 for the baseline).

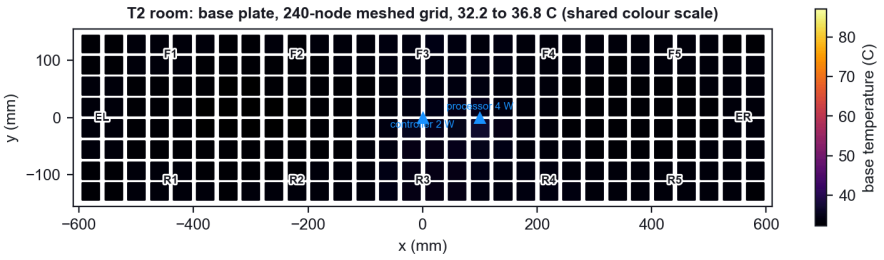


In plain terms: Brightness of the whole bar all the way around the vehicle; every dot must sit above the dashed line. Full-bar 360-degree coverage (12 modules of C1, 72 dies, bar base, top cover and perimeter outer lens) as luminous intensity vs horizontal angle H (0 = vehicle forward, clockwise toward +x): shaded band = range of the 1 x 1 deg cells over V -10..+10 deg (pooled mean), line = the dimmest cell at each H, dots = the 120 assembly mask points as lower 95% bounds against the dashed 1.1 x target line. The front and rear dips at V = 0 are the module beam's two vertical lobes (peaks near V +/-5 deg). Pulse-on output scaled to the weakest module's radiant output in the stated thermal state. Simulated, Paraxial non-sequential engine, 70/90 seeds x 2 M rays per colour (red/blue), Simple Splitting; synthetic mask (100 cd red, 40 cd blue), not SAE J845.

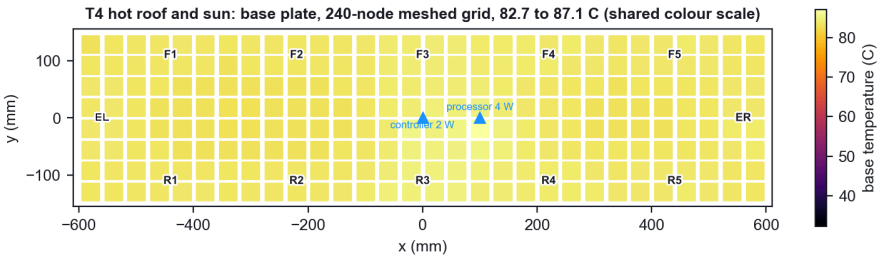
Colour	Worst bar margin (0.7 A, 25 C)	at (H, V)	At the selected current, hot roof	95% half-width	Darkest directions (V +/-10)	Share above horizontal	Absorbed in bar body
red	3.22	(-90, 0)	2.01	4.6%	H 90, V -1: 319 cd; H -90, V 1: 322 cd	43.4%	5.0%
blue	3.95	(-90, 0)	1.85	4.5%	H -90, V 1: 160 cd; H -91, V 2: 161 cd	43.4%	5.0%

Full 12-module bar of the selected optic: 120 mask points every 15 deg around the vehicle at V = -10..10 deg. Hot-roof value = normalisation margin x the weakest module's pulse-on output at the selected current.

4. Thermal operating states

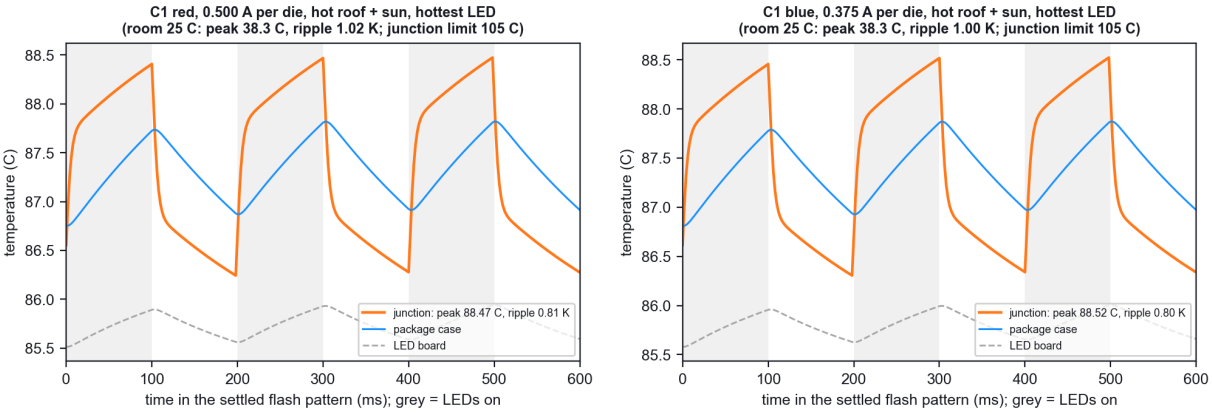


LED R3I0 heat path (nodes)		
junction (avg)	37.3 C	4 K/W limit 105 C
LED board	35.7 C	2 K/W
module spreader	34.9 C	TIM 0.185 K/W
base (max)	36.8 C	h, radiation
internal air	31.1 C	
polymer lens	33.6 C	limit 85 C
metal reflector	34.8 C	bracket 0.5 W/K
top cover (max)	28.0 C	limit 85 C
outer lens	28.4 C	limit 85 C
air 25 C / roof 25 C		boundaries



LED R3I0 heat path (nodes)		
junction (avg)	87.7 C	4 K/W limit 105 C
LED board	86.0 C	2 K/W
module spreader	85.2 C	TIM 0.185 K/W
base (max)	87.1 C	h, radiation
internal air	81.3 C	
polymer lens	83.9 C	limit 85 C
metal reflector	85.1 C	bracket 0.5 W/K
top cover (max)	79.3 C	limit 85 C
outer lens	71.8 C	limit 85 C
air 65 C / roof 85 C		boundaries

In plain terms: Temperatures across the whole bar, room vs hot roof. Thermal operating states of the full bar, C1 red channel at 0.50 A per die, 100 ms on / 100 ms off (duty-averaged steady state), room (T2) vs hot roof and sun (T4). Left: base-plate temperature from the meshed 30 x 8 node grid (spatial calculation; mesh refinement in validation). Right: the hottest LED's heat path as network nodes, not an interpolated field. Simulated on Paraxial FEA solver; coupled with optical output eta(Tj) and absorbed light from the NSC ledger. Key assumptions A09-A19 (internal air h = 3 W/m2K, optic mount 0.05 W/K). Uncertainty: boundary coefficients swept x0.5/x2 in the sensitivity figure.



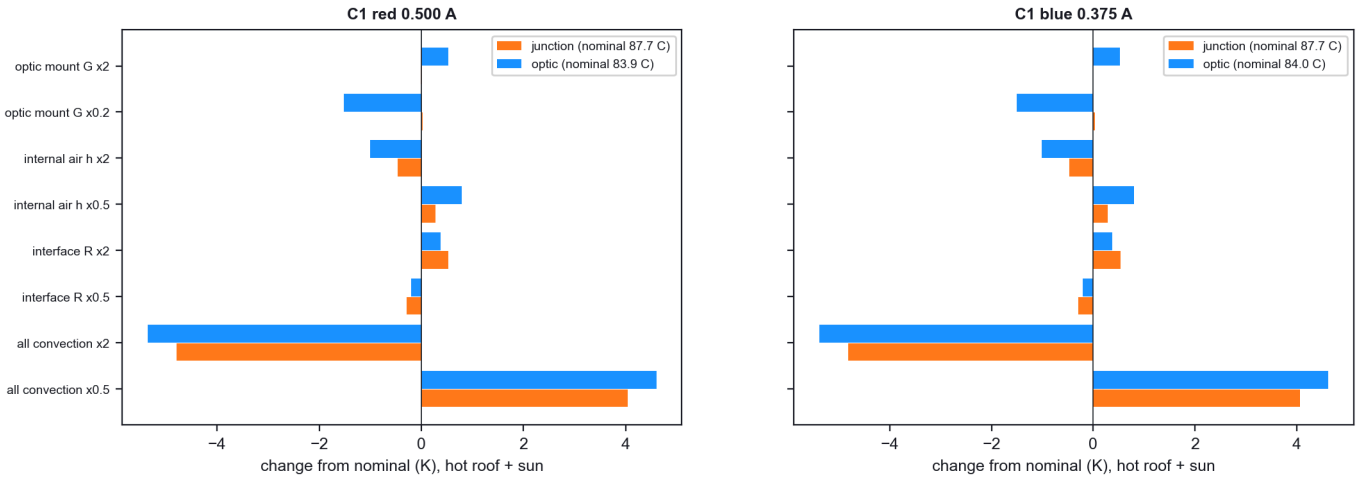
In plain terms: The LED chip's temperature through three flashes on the hot roof. Junction, package-case and LED-board temperature of the hottest LED through three flash periods (100 ms on / 100 ms off) in the hot roof + sun case (T4); the room case (T2) is quoted in each title. Transient solve (BDF2, 2 ms step, states stored every 2 ms) over 2 s (10 flash periods) from the duty-averaged steady state of the coupled network; the last 0.6 s is shown (end-of-period drift in pulse_series.json). The junction ripple is small because the package and board heat capacities (assumption A18) average the flashes. Simulated, Paraxial FEA solver.

Colour	Current	Case	Junction pulse peak (C)	Polymer lens (C)	Outer lens / cover (C)	Reflector (C)	Electronics (C)	Worst margin	Useful lm / module
red	0.500 A	T1	-23.8	-28.6	-34.9 / -36.7	-27.0	-26.9	1.56	264
red	0.500 A	T2	38.1	33.6	28.4 / 28.0	34.8	34.9	1.39	234
red	0.500 A	T3	76.5	72.2	67.6 / 67.7	73.3	73.3	1.28	215
red	0.500 A	T4	88.5	83.9	71.8 / 79.3	85.1	85.2	1.24	210
red	0.500 A	T5	84.2	79.0	67.1 / 70.2	80.7	80.9	1.25	212
blue	0.375 A	T1	-24.0	-28.6	-34.9 / -36.7	-27.0	-26.9	1.39	96
blue	0.375 A	T2	38.1	33.7	28.4 / 28.0	34.9	35.0	1.23	86
blue	0.375 A	T3	76.6	72.3	67.6 / 67.8	73.4	73.4	1.14	79
blue	0.375 A	T4	88.5	84.0	71.8 / 79.3	85.2	85.3	1.11	77
blue	0.375 A	T5	84.2	79.1	67.1 / 70.3	80.8	81.0	1.12	77

Selected design at its operating currents in every thermal case, warning duty (100 ms on / 100 ms off). Pulse peak = duty-averaged state + ripple from the settled pulsed window. Electronics = module spreader carrying the driver.

Where the change came from. From room to hot roof at the same current, the pulse-on output of the weakest red module falls 10.4%: that loss is heat (junction temperature), while the hot optics themselves (index change and thermal growth) change the useful flux by +0.3%. Against A1, the lowest-power alternative that also passes, the saving comes from optical collection: at the same 0.7 A and 25 C its worst red margin is 1.99 against 1.06, so it reaches the target at a lower drive current (red 0.500 A vs 0.900 A, blue 0.375 A vs 0.700 A), and the bar average falls from 93 W to 52 W. Heat removal is the remaining lever: an isolated lens mount (0.01 instead of 0.05 W/K, assumption A19) lowers the hot-roof lens temperature by 1.6 K at blue 0.400 A, which keeps blue 0.450 A (margin 1.32) inside the 85 C limit.

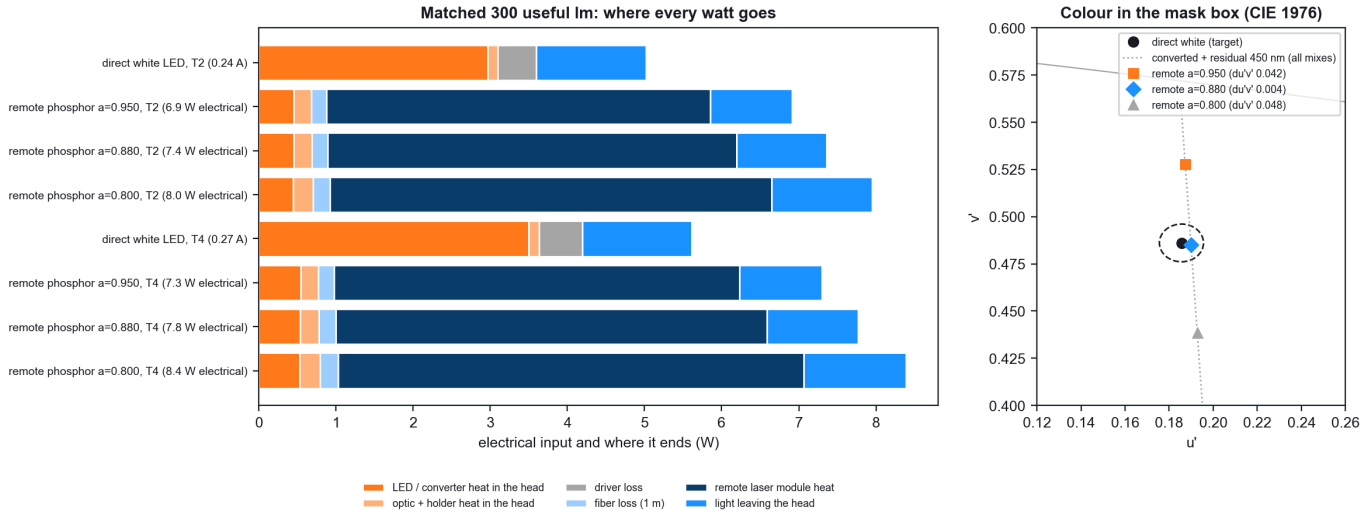
What the heat does to the light (C1, red 0.50 A, hot roof + sun). Source derating is the dominant effect: at the pulse-peak junction temperature the LEDs emit 12.7% less than at 25 C. The polymer index change (lens n = 1.4841, outer lens n = 1.4853 at their solved temperatures) moves the useful flux by +0.24%; adding thermal growth of the lens, its mount gap and the reflector moves it by +0.31% (mean mask-cell change +0.14%). Refraction and deformation are an order of magnitude smaller than derating in this design.



In plain terms: How far each uncertain cooling assumption moves the LED and lens temperatures. Thermal sensitivity of the finalists in the hot-roof + sun case at the warning duty: every convection coefficient x0.5 / x2, the module interface resistance x0.5 / x2, the internal-air coefficient alone x0.5 / x2 (assumption A13) and the optic mount conductance x0.2 / x2 (assumption A19). Coupled network (eta(Tj) iterated), Paraxial FEA solver. Bars show the change from nominal; the largest bar is the assumption the result is most sensitive to. None of these coefficients is a Federal Signal number.

Most uncertain boundary condition. The polymer lens in the hot-roof case has 1.0 K of headroom to 85 C. It is most sensitive to every convection coefficient (outside and inside; proposed demonstration values): x0.5 raises it +4.6 K (blue, to 88.6 C, past the limit); the full range over x0.5 to x2 is -5.4 to +4.6 K. The others move it less: the internal-air coefficient alone (A13) -1.0 to +0.8 K; the optic mount conductance (A19) -1.5 to +0.5 K; the module interface resistance -0.2 to +0.4 K. None of these is a Federal Signal number.

5. Remote-source comparison (white light)



In plain terms: Where the power goes in the two white-light options, and whether their colour matches. White-light heads matched to 300 useful lm (H +/-45 deg, V +/-10 deg, within 2%%), continuous drive: direct white LED head vs fiber-fed remote phosphor (450 nm laser, 1 m fiber, 2 x 2 mm converter, same optic family), at room (T2) and hot roof + sun (T4). Heat at every location: head (converter or LEDs, optic, holder), driver, fiber, remote laser module. Converter pump absorption a = 0.95 (seed value), 0.80 and 0.88 (traced loadings bracketing and matching the colour); the dotted line is every colour reachable by changing the residual pump. Right: chromaticity of the light in the mask box vs the direct-white spectrum (circle: du'v' = 0.01). Simulated: optics Paraxial non-sequential engine (two-stage trace, photon accounting QY(T)), heat Paraxial FEA solver. Remote laser module location and mounts are assumptions (A16).

Head	Case	Electrical (W)	lm vs 300	du'v'	Head heat (W)	Remote heat (W)	Fiber loss (W)	Optic heat (W)	Residual pump in box (W)	Temperatures (C)	White mask margin
direct white LED	T2	5.0	+0.82%	0 (target)	3.69	0	0	0.13	0	Tj 33.4, lens 29.1	1.76
remote phosphor, a = 0.950	T2	6.9	+0.50%	0.0431	0.68	4.98	0.19	0.10	0.071	converter 31.2, lens 27.1, laser module 37.5	1.94
remote phosphor, a = 0.880	T2	7.4	+0.50%	0.0047	0.69	5.30	0.21	0.10	0.183	converter 31.1, lens 27.1, laser module 37.6	1.94
remote phosphor, a = 0.800	T2	8.0	+0.50%	0.0433	0.70	5.73	0.22	0.11	0.330	converter 31.1, lens 27.1, laser module 37.9	1.90
direct white LED	T4	5.6	+0.67%	0 (target)	4.29	0	0	0.13	0	Tj 86.0, lens 80.9	1.75
remote phosphor, a = 0.950	T4	7.3	+0.52%	0.0416	0.77	5.25	0.20	0.10	0.075	converter 83.8, lens 78.8, laser module 37.6	1.94
remote phosphor, a = 0.880	T4	7.8	+0.52%	0.0044	0.78	5.59	0.22	0.10	0.193	converter 83.8, lens 78.8, laser module 37.8	1.94
remote phosphor, a = 0.800	T4	8.4	+0.52%	0.0482	0.79	6.04	0.23	0.11	0.348	converter 83.7, lens 78.8, laser module 38.0	1.89

300 useful lm in H +/-45, V +/-10 deg, continuous drive, same optic family in the same envelope. Converter 2 x 2 mm with pump absorption a (bulk absorption in the converter, traced); converted power = absorbed pump x QY(T) x photon-energy ratio 0.8036 (450 nm pump, 560/100 nm emission). Laser-module temperature uses the assumed remote mount (A16).

What the comparison shows (hot roof + sun). The colour target is only met with the right converter loading: a = 0.950 misses by du'v' = 0.042; a = 0.800 misses by du'v' = 0.048, against a tolerance of 0.01, because the residual blue pump that leaks through sets the white point. The agent traced a converter absorbing 88% of the pump, which matches (du'v' = 0.0044). At that matched point, moving the source moves most of the heat out of the head: the direct white head dissipates 4.3 W in the head, the remote head 0.8 W (converter 0.54 W, optics 0.10 W). The rest of the remote head's input becomes heat elsewhere: 5.6 W at the remote laser module and 0.22 W along the fiber. System input rises from 5.6 W to 7.8 W.

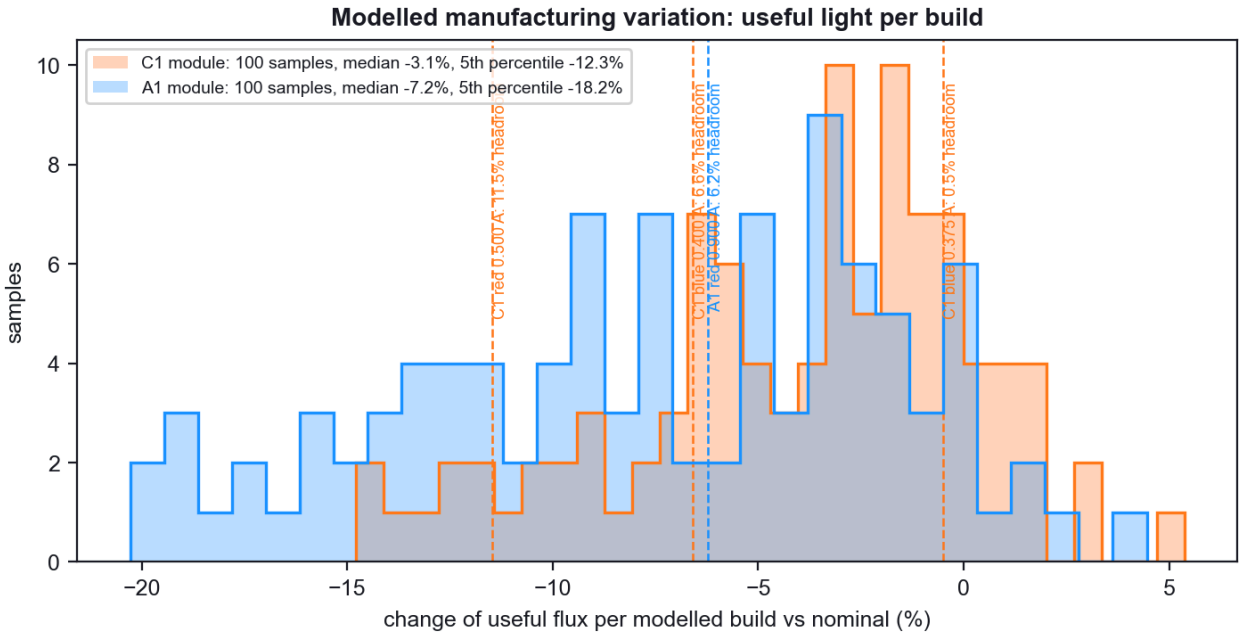
Sensitivity, remote head a = 0.880, hot roof	Electrical (W)	Within 20 W	Converter (C)	Head heat (W)	Remote heat (W)
fiber transmission=0.70	10.0	yes	83.8	0.78	7.19
fiber transmission=0.90	7.8	yes	83.8	0.78	5.59
fiber transmission=0.98	7.1	yes	83.8	0.78	5.13
quantum yield=0.70	10.0	yes	88.1	1.29	7.19
quantum yield=0.90	7.8	yes	83.8	0.78	5.59
quantum yield=0.98	7.1	yes	82.5	0.64	5.14
source efficiency=0.25	10.9	yes	83.8	0.78	8.70
source efficiency=0.35	7.8	yes	83.8	0.78	5.59
source efficiency=0.45	6.0	yes	83.8	0.78	3.87

For a qualified product-safety review (this is not a laser-safety classification). The pump is a 450 nm laser delivered through a 1 m, 0.6 mm core, NA 0.22 fiber. A detached or cracked converter or a fiber break at the head could expose laser light that is far more radiant than the residual pump listed above. A product would need converter-presence and fiber-continuity interlocks, a laser-safety classification of the complete assembly, and the colour and photometric standard of its lighting function. White-light results here are not evidence for the red or blue warning functions. Model-health note: the collision check flags the fiber ferrule passing through the head's mounting board; both parts are opaque and the overlap is enclosed, so no ray reaches it.

6. Evidence and the next engineering decision

Check	Result	Reference or gate	Evidence type	Status
Lambertian source, 1 W	power on sphere 1.000000 W; 25.08% in 30 deg (0.8 sigma)	1 W; 25%	analytical	pass
H +/-45, V +/-10 fraction	0.155462 (2 M rays)	0.155549 (-0.34 sigma)	analytical	pass
n = 1.49 slab	T 0.925435, R 0.074563	0.925437 / 0.074563	analytical	pass
Mirror 0.90, mesh and primitive	0.900 reflected, 0.100 absorbed	0.9 / 0.1	analytical	pass
Bulk absorption 100 mm at 0.01/mm	absorbed 0.607642	0.607642	analytical	pass
Mesh solid vs primitive slab	0.925435	0.925435	engine cross-check	pass
Cell solid angle	max error 1.3e-14	dH (sin Vhi - sin Vlo)	analytical	pass
Independent far-field reference (bare LEDs, matched physics)	useful flux +0.14%, mean cell +0.36%	<= 3% flux, <= 5% at required angles	independent calculation	pass
Same, with board/package recycling left in	useful flux +3.1% (red)	explained: the reference omits recycled light	independent calculation	explained
Full ghost splitting vs Simple Splitting (C1)	useful 0.5432 vs 0.5435, absorbed 0.1477 vs 0.1479	same physics, different estimator	engine cross-check	pass
Geometry refinement (2x tessellation, C1)	useful +0.04%, mean cell +0.68%	<= 2%	convergence	pass
LED network fixture (65 C, 0.7 A)	Tj 114.84677506 C, base 107.88066454 C	114.84677506 / 107.88066454	analytical	pass
Time step 2 ms -> 1 ms (pulse peak)	pulse-peak junction changes 0.018 K (C1 blue 0.70 A, hot roof)	<= 1 C	convergence	pass
Thermal mesh 20 x 5 -> 30 x 8	junction 0.48 K, lens 0.39 K (C1 blue 0.70 A, hot roof)	<= 2 C	convergence	pass
Energy ledgers	optical closure < 1e-11 %; thermal mismatch < 1e-12	<= 0.5 %; <= 2 %	conservation	pass
Same-seed repeat	bit-identical	<= 1e-6	reproducibility	pass
Mask-cell uncertainty (finalists)	<= 4.4% relative 95% half-width	<= 5%	statistics	pass

No measured Federal Signal data and no external commercial solver were available: correlation against a measured bar is the next step. Simulation-to-simulation agreement is reported separately from measurement correlation.



In plain terms: How much useful light each simulated build loses; builds left of a dashed line would fall short at that setting. Modelled manufacturing variation of the finalist modules (red): 100 samples each with independent uniform perturbations (LED package placement x/y/z +/-0.10 mm with its dies, die flux +/-10%, optic displacement +/-0.20 mm and tilt +/-1 deg about x and z through the module origin, reflectance +/-0.02). Each sample is a fresh copy of the qualified scene traced with 1 M rays and the nominal's seed. Plotted: change of the useful flux in H +/-45, V +/-10 deg (an integral, ray noise about 0.2%). Dashed lines: the light headroom above the 1.1 margin of each operating point in the hot-roof case; a build losing more than that would fall below 1.1 if the loss were spread evenly over the mask. Per-cell margins were also computed, but at 1 M rays per sample the per-cell ray noise (median 6%, up to 13%) is as large as the effect, so they are not used. This is modelled sensitivity under assumed independent distributions, not a production yield. Simulated, Paraxial non-sequential engine.

Design	Single change (same seed as nominal)	Useful flux change
A1 red	LED packages +0.1 mm (x, y, z)	-1.6%
A1 red	LED packages -0.1 mm (x, y, z)	+1.1%
A1 red	reflector +0.2 mm (x, y, z) and +1 deg tilt (x, z)	-18.7%
A1 red	reflectance -0.02	-1.7%
C1 red	LED packages +0.1 mm (x, y, z)	-1.1%
C1 red	LED packages -0.1 mm (x, y, z)	+1.0%
C1 red	reflector +0.2 mm (x, y, z) and +1 deg tilt (x, z)	-12.3%
C1 red	lens +0.2 mm (x, y, z) and +1 deg tilt (x, z)	-0.1%
C1 red	reflectance -0.02	-1.3%

One factor at a time at its tolerance limit, 1 M rays with the nominal's seed (common random numbers). Simulated, Paraxial non-sequential engine.

Manufacturing sensitivity (modelled, not a yield). Useful light per modelled build: C1 module: median -3.1%, 5th percentile -12.3%, worst -14.8% over 100 builds; A1 module: median -7.2%, 5th percentile -18.2%, worst -20.3% over 100 builds. The largest single effect is reflector +0.2 mm (x, y, z) and +1 deg tilt (x, z) (A1 red, -18.7%). Against each operating point's light headroom above the 1.1 margin in the hot-roof case: C1 red 0.500 A (11.5% headroom): 8% of builds lose more; C1 blue 0.375 A (0.5% headroom): 80% of builds lose more; C1 blue 0.400 A (6.6% headroom): 23% of builds lose more; A1 red 0.900 A (6.2% headroom): 55% of builds lose more. Blue uses the red module's distribution (same optic). Per-cell margins were also computed, but at 1 M rays per sample their ray noise (median 6%, up to 13% per cell) is as large as the effect, so they are not used; resolving them needs about 10 M rays per sample. These are assumed independent uniform tolerances, so the fractions are sensitivity statements, not production yields.

What the result rests on. Synthetic LED data, a synthetic angular mask and assumed thermal boundary values (appendix B). Each is an input to the same model: replacing one re-runs every check in this report.

7. Robust design D2: isolated lens mount

Design. D2 is the C1 optic with the isolated lens mount (assumption A19: 0.01 instead of 0.05 W/K between each module's lens and its LED spreader), red 0.55 A and blue 0.45 A per die. The optic, geometry, drive waveform, thermal cases and requirements are those of D1. The thermal states use the same network, loads and solver settings as section 4 (Paraxial FEA solver): blue at the isolated mount (0.40 and 0.45 A) was solved on 2026-10-28; red at the isolated mount (0.50 and 0.55 A), the high-resolution pulse windows and the boundary sensitivity of every D2 point were solved on 2026-11-02.

How the currents were chosen. Per colour, the lowest isolated-mount current that passes every case and leaves more light headroom (1 - 1.1 / worst margin, hot roof) than any of the 100 modelled builds lost (worst 14.8%). Evaluated: blue 0.4 A: passes every case, margin 1.177, 6.6% headroom, 23 of 100 builds short; blue 0.45 A: passes every case, margin 1.321, 16.7% headroom, 0 of 100 builds short; red 0.5 A: passes every case, margin 1.242, 11.5% headroom, 8 of 100 builds short; red 0.55 A: passes every case, margin 1.364, 19.3% headroom, 0 of 100 builds short. Selected: red 0.55 A, blue 0.45 A.

Colour	Current	Case	Tj peak (C)	Lens (C)	Outer lens / cover (C)	Reflector (C)	LED board (C)	Module margin	Bar margin	Useful lm
red	0.55 A	T1	-22.5	-29.8	-34.5 / -36.5	-26.0	-25.8	1.71	2.77	289
red	0.55 A	T2	39.2	32.7	28.6 / 28.2	35.6	35.7	1.52	2.46	257
red	0.55 A	T3	77.6	71.4	67.8 / 67.9	73.9	74.0	1.40	2.26	236
red	0.55 A	T4	89.5	82.9	72.0 / 79.4	85.7	85.9	1.36	2.20	230
red	0.55 A	T5	85.1	77.2	67.1 / 70.3	81.3	81.5	1.38	2.23	232
blue	0.45 A	T1	-21.3	-29.0	-34.2 / -36.2	-25.0	-24.8	1.66	2.78	115
blue	0.45 A	T2	40.3	33.4	28.9 / 28.5	36.4	36.5	1.47	2.46	102
blue	0.45 A	T3	78.6	72.0	68.0 / 68.2	74.7	74.7	1.36	2.27	94
blue	0.45 A	T4	90.5	83.4	72.2 / 79.7	86.5	86.5	1.32	2.21	92
blue	0.45 A	T5	86.1	77.7	67.2 / 70.4	82.0	82.1	1.33	2.23	93

D2 operating states, warning duty (100 ms on / 100 ms off). Module margin: lowest lower-95% bound / target over the 35 mask points, pulse-on at the pulse-peak junction temperatures. Bar margin: worst of the 120 bar directions (normalisation trace) x the weakest module's output in that case.

Gate (same rule as D1)	D1	D2	Status
Module mask, lower 95% >= 1.1 x target, all cases	red 1.242 / blue 1.106	red 1.364 / blue 1.321	met
Full bar, 120 directions >= 1.1 x target	red 2.01 / blue 1.85	red 2.20 / blue 2.21	met
Full bar, largest 95% half-width <= 5%	4.6% / 4.5%	same traces	met
Junction <= 105 C (pulse peak)	88.5 C	90.5 C	met
Polymer parts <= 85 C	84.0 C (lens)	83.4 C (lens)	met
Bar average <= 100 W, peak <= 200 W	52 / 99 W	62 / 118 W	met
Module peak <= 15 W	8.2 W	9.8 W	met
Modelled builds below 1.1 (red / blue)	8 / 80 of 100	0 / 0 of 100	reported

Worst over the five thermal cases and both colours.

Point (hot roof)	Lens (C)	LED board (C)	Internal air (C)	Absorbed light (mW)	Through mount (mW)	To internal air (mW)	Balance residual (W)
D1, blue 0.375 A, standard mount	83.98	85.30	81.40	3.9	65.9	69.8	4e-15
blue 0.45 A, standard mount	85.07	86.52	82.23	4.6	72.3	76.9	1e-16
D2, blue 0.45 A, isolated mount	83.42	86.55	82.09	4.6	31.3	35.9	3e-16
D2, blue 0.45 A, all convection x0.5	88.45	90.74	86.40	4.6	23.0	27.6	7e-09

Steady heat balance of the hottest lens node at the warning duty, from the solved node temperatures and the network's own conductances: mount (A19), lens-to-air convection (A13, 0.027 W/K) and the absorbed light applied from the trace ledger (4.4% of the optic absorption goes to the lens, A20).

Variation (hot roof)	D1 lens (C)	D2 lens (C)	D1 Tj avg (C)	D2 Tj avg (C)	D2 internal air (C)
as modelled	84.0	83.4	87.7	89.5	82.1
all convection ×0.5	88.6	88.4	91.8	93.7	86.4
all convection ×2	78.6	78.0	82.9	84.4	77.3
air inside ×0.5	84.8	84.4	88.0	89.7	82.3
air inside ×2	83.0	82.6	87.3	89.0	81.9
lens mount ×0.2	82.5	82.5	87.8	89.5	82.0
lens mount ×2	84.5	84.1	87.7	89.4	82.1
LED interface ×0.5	83.8	83.3	87.4	89.1	82.0
LED interface ×2	84.4	83.7	88.3	90.1	82.2

Boundary and interface sensitivity, warning duty, worst of both colours. The convection coefficients and A13/A19 are proposed demonstration values.

Pulse windows and reuse. The settled 2 s high-resolution window of D2's hotter colour (blue 0.45 A, hot roof) peaks at 90.47 C with 1.01 K ripple. The full-bar traces (70 red and 90 blue seeds of 2 M rays) and the 100 modelled builds are optical results at the 0.7 A / 25 C normalisation; the lens mount changes the heat path, not the geometry, so both are reused and scaled by D2's own weakest-module output in each case, exactly as for D1. As for D1, the builds were traced in red and their useful-flux losses are applied to both colours.

Most sensitive input. The lens stays the binding part (1.6 K below 85 C). With every convection coefficient halved, the internal air reaches 86.4 C and the lens 88.4 C in both designs, so on a hot roof the result depends most on the bar's real convection; the lens mount then matters little because the air itself is above the limit.

Appendix A. Requirement-by-requirement completion

Requirement	Evidence in this study	Status
FS01 thin bar, finite emitters	12-module 3D assembly and module scenes (scene documents, STEP archives), 0.9 mm equal-area disc dies for the 0.8 mm square dies, collision and model-health checks	met (simulated)
FS02 useful light at required directions	absolute candela maps, 35 module + 120 bar mask cells with lower 95% bounds, darkest directions, full-sphere ledger incl. rearward and absorbed per part	met (simulated)
FS03 heat with LEDs, processors, roof gap	coupled thermal network of the bar: LED packages, drivers, controller, processor, roof radiation, sun, convection; power ledger	met (simulated)
FS04 cold to hot environments, pulses	same fixed targets in T1-T5, settled pulse peaks, derating and hot-state optics	met (simulated)
FS05 agent explores designs	177 parametric designs generated in three architectures (3 rejected by the geometry check), 174 traced in screening and refinement, 3 qualified finalists plus the baseline, rejection reasons, option points (intermediate currents, isolated lens mount, higher A1 current), trade-off and sensitivities	met
FS06 fiber + remote phosphor	matched 300 lm white heads, two-stage converter trace, photon accounting, heat at every location, colour, sensitivity, safety assumptions	met (simulated)
FS07 faster useful iteration	Design screening: 174 designs traced at 1 M rays each in 17 min 44 s (6.1 s per design). Detailed iteration timing on the module is available on request	met
FS08 fits the workflow	engine exports of the selected module, the full bar and the remote head: STEP archives (module: 11 B-rep solids, 3 meshed optics as STL inside the archive) and SDK scripts that rebuild each scene; portable scene documents; editable intent and method files. Supplier ray files cannot yet be loaded (engine limit)	partly met

Appendix B. Assumptions added by this study

Id	Item	Value	Why
A01	Die emitting shape	Lambertian disc of equal area to 0.8 x 0.8 mm (diameter 0.9027 mm); 90 deg cut-off	Rectangular sources are not available in the engine build; far-field Lambertian distribution is shape-independent
A02	Dies per package	red, blue and white dies at local x offsets -1.0, 0, +1.0 mm; only the selected channel emits	study_spec color_die_local_x_offset_mm
A03	Package body	3.5 x 3.5 mm footprint, 0.8 mm deep behind the die plane, opaque absorptance 0.7	Representative ceramic LED package; obscuration and absorption
A04	LED board	1.6 mm board behind the packages across the module (180 x 27 mm), opaque, absorptance 0.3 (white solder mask)	Representative; board reflectance affects recycling
A05	Outer lens (cover)	2 mm generic polymer wall at the bar perimeter: module local y 35.5..37.5 for front/rear modules; bar top cover z 31..33	Bar 295 mm deep, modules at y = +/-110 with 45 mm depth
A06	Polymer optics	n = 1.49 constant over wavelength at 25 C; dn/dT -1e-4/K; CTE 70e-6/K; bulk absorption 0.001/mm as the material's native bulk_absorption (coefficient), verified against Beer-Lambert on a 100 mm rod (engine 0.607642 vs analytic 0.607642)	Spec values. The add-material route drops bulk_absorption; it is set through the scene document
A07	Reflector	0.90 specular reflectance (ideal coating) on a triangle-mesh surface, both sides	Spec value
A08	Photometry	Candela and chromaticity from CIE 018:2019 1 nm tables (hash-verified) applied to the channel spectrum; engine photometry used as a cross-check	Engine V(lambda) is a 10 nm interpolated table (+1.45% on blue)
A09	Thermal path per LED	junction-to-board 4 K/W (JEDEC 2R) + local board-to-base 2 K/W per LED onto the module spreader node, then the module interface 0.5 mm, k 1.5 W/mK, 1800 mm2 (0.185 K/W) to the meshed base	Spec values; local path not duplicated in the base mesh
A10	Drivers and controls	driver loss at 90% efficiency located on each module's spreader node; controller 2 W and processor 4 W on the base at x = 0 and x = +100 mm (design variables)	Spec values; placement assumed
A11	Roof interaction	25 mm gap; base underside to roof radiation (emissivity 0.85 both, view factor from geometry); underside convection h = 3 W/m2K to air; 4 mounting feet, 20 x 20 mm polymer pads, 25 mm tall, k 0.2 W/mK	Spec boundary values; feet assumed
A12	Sky	top and sides radiate to surroundings at air temperature	Conservative for hot cases; a cold sky would cool the bar
A13	Internal air	enclosed air between base and cover: one air node, h = 3 W/m2K to base top and cover underside; base-top to cover radiation emissivity 0.85	Not specified; natural convection in a 28 mm cavity
A14	Solar	1000 W/m2 x effective absorptivity 0.2 on the projected top area, absorbed in the top cover	Spec value
A15	Source output vs temperature	eta(Tj) = eta25 (1 - 0.002 (Tj - 25)); pulse-on intensity evaluated at the pulse-peak junction temperature (end of the on-pulse, worst case)	Spec fixture; conservative choice of instant
A16	Remote source	450 nm laser, fiber exit = 0.6 mm Lambertian disc cut at 12.709 deg (NA 0.22); converter 2 x 2 mm, pump absorbed in the 0.2 mm converter volume by native bulk absorption (coefficient -ln(1-a)/0.2 per mm, traced; a = 0.95 seed value; 0.80 and 0.88 also traced; 0.88 matches the white colour), converted light = finite Lambertian re-emitter with the remote_converted spectrum; remote laser module mounted inside the vehicle at 35 C ambient on a 0.5 K/W heat sink; converter mounted on a heat spreader to the head base, 8 K/W	Spec seeds; locations and thermal paths assumed
A17	Bar base top surface	opaque, absorptance 0.8 (dark finish)	Not specified; affects stray recycling and base heating

A18	LED transient thermal masses	junction 0.002 J/K, package (case) 0.02 J/K on R_jc = 4 K/W, LED board-local node 0.05 J/K	Not specified; sets the pulse ripple; replace with the supplier's transient thermal impedance
A19	Optic mount conductance	0.05 W/K from each module's optic (lens/reflector) to its LED spreader; isolated-mount variant 0.01 W/K	Not specified; found to control the polymer lens temperature in the hot-roof case
A20	Reflector thermal mount	metal reflector node per module, 0.5 W/K bracket to the LED spreader, 0.5 mm aluminium sheet thermal mass; receives the reflector's absorbed light (95.6% of C1's optic absorption; lens 4.4%)	Not specified; separates metal reflector heat from the polymer lens (corrected 2026-10-28: an earlier lumped optic node over-heated the lens)

Appendix C. Modelling choices

- LED dies are modelled as Lambertian discs of equal area to the 0.8 x 0.8 mm dies (0.903 mm diameter). Supplier ray files or IES data would replace them.
- Photometric and colour quantities use the CIE 018:2019 photopic V(lambda) and CIE 1931 2-degree tables at 1 nm.
- Every optical result pools independent seeded traces of 2 M rays each; mask checks use the lower 95 % bound of the t-distribution over seeds, with a 5 % half-width gate.
- The remote-phosphor head is traced in two stages, the blue pump through the converter and then the converted light, with photon accounting between them.
- Module studies use source spectra at 1 nm; the assembled 12-module bar uses the same spectra sampled at 5 nm.
- The base plate is meshed at about 40 mm (30 x 8 nodes); halving the mesh size changed the hottest junction by 0.48 K and the lens by 0.39 K.
- Pulse peaks come from a 2 s transient window (100 ms on / 100 ms off) started from the duty-averaged state; the last flashes are settled to within 0.03 K per period.