# BARRETT IO-540-D4A5 — SDS EFI ENGINE STATE & TUNING HISTORY

**Aircraft:** Barrett IO-540-D4A5, 9:1 CR, 6-cyl | **EFI:** SDS Model F Fuel & CPACK Ign | **SW 33.4 O2:** AEM (NEW) WB 0-5V — verified working (responds correctly to mixture sweep) **Last updated:** 2026-06-06 | **Current loaded ECU:** ECU21 — SETTLED BASELINE (flight-tested to 8500ft) | **ROP: complete & locked. LOP: complete** (procedure: Garmin Lean Assist → LOP → trim to 15.4 AFR; % varies with altitude by design)

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## HOW THE FUEL SYSTEM WORKS (the rule we keep)

Fuel delivered = **RPM_table[rpm] × MAP_table[map] × baro_comp × cylinder_trims** The RPM table sets base injector pulse at each RPM; the MAP table scales fuel across load. **They work together — a MAP cell cannot be read or changed without its RPM-table partner.** AFR is what the engine actually runs; the tables must be judged by the AFR they produce per phase.

## THE CORRECTION FORMULAS (how each ECU is computed)

### 1. Fuel delivery model

Fuel pulse delivered = RPM_fuel[rpm] x MAP_fuel[map] x baro_comp x cyl_trim

- baro_comp = 1 + 0.007 x (altitude_ft / 1000)   [0.7%/1000ft]
- cyl_trim = per-cylinder %, currently near 0 (kept minimal for GAMI)

### 2. Predicting AFR from the tables (verified speed-density model)

AFR = C(rpm) x RPM x MAP_inHg / (RPM_fuel x MAP_fuel x baro_comp)

- C(rpm) is the engine's calibration curve (lumps volumetric efficiency). Derived empirically from ~26,000 pooled rich-of-peak (AFR<=13.5) rows across all flights. C falls as RPM rises (engine breathes differently): roughly 8.6 at idle down to ~3.5 at takeoff.
- Verified to within 0.25 AFR across taxi, cruise, climb, takeoff.

### 3. The core correction (used every ECU revision)

When a cell ran at observed AFR but you want a target AFR: NEW_fuel = OLD_fuel x (observed_AFR / target_AFR)

Direction check (AFR is inversely proportional to delivered fuel — more fuel = lower/richer AFR):

- If it ran LEANER than goal (observed > target): ratio > 1 -> ADD fuel -> AFR comes down to target.
- If it ran RICHER than goal (observed < target): ratio < 1 -> CUT fuel -> AFR comes up to target.

Worked examples (actual ECU21 build, 2026-06-06 data):

- Cruise 2400: ran rich at 12.0, goal 13.5 (lean it). NEW = 191 x (12.0/13.5) = 170. Less fuel. ✓
- Taxi 1000: ran rich at 13.2, goal 13.5. NEW = 139 x (13.2/13.5) = 136. Less fuel. ✓
- Climb 2500: ran 10.2 at the 220 cell; goal is 10.0 (best cooling) — essentially on goal, held at 220. (Note: climb goal is 10.0 BEST COOLING, not 11.0. Earlier drafts used 11.0; superseded.)

## 4. Removing influences before correcting (critical)

- Remove the pilot's manual SDS trim knob: base_AFR = observed_AFR x (1 + trim_fraction) (e.g. -35% trim and observed 12.0 -> base = 12.0 x 0.65 = 7.8)
- Remove LOP lean (-19%) to get ROP-equivalent: ROP_AFR = LOP_AFR x (1 - 0.19) = LOP_AFR x 0.81
- Only use SETTLED rows, never transient lean-sweep rows.

## 5. The two-table architecture (how a shared MAP cell serves two phases)

- MAP table = smooth monotonic AIR curve (linear ramp ~5.4 x MAP - 30). No AFR baked in.
- RPM table = the AFR lever, solved per phase: RPM_fuel = C(rpm) x rpm x MAP_at_that_phase / (target_AFR x MAP_fuel)
- Same MAP cell (e.g. 15") gives 13.5 at taxi RPM-fuel AND 12.0 at cruise RPM-fuel, because the two RPM-fuel cells differ. RPM table need NOT be monotonic.

## AFR GOALS (ROP + LOP — both flown)

| Phase | RPM | Target AFR | Note |
|---|---|---|---|
| Ground/Taxi | 700-1300 | 13.5 | below this fouls plugs |
| Takeoff | 2600-2700 | 10.0-11.0 | best cooling |
| Climb WOT | 2500 | 10.0 (best cooling) | |
| Cruise | 2200-2400 | 13.5 | best SPEED (was 12.0 best power; ~1-2kt faster, leaner, cooler) |
| LOP cruise | 2200-2400 | 15.4 | 45-50°F LOP; flown 2026-06-06, see LOP section |

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## ECU VERSION HISTORY (matched to flight logs)

| **ECU** | **RPM 2500/26/27** | **MAP 15.0"** | **MAP 19.0"** | **baro** | **Notes / Result** |
|---|---|---|---|---|---|
| 11 | 230/232/238 | 53 | 69 | 1.5% | smooth MAP, early |
| 12 | 204/195/195 | 53 | 71 | 1.5% | smooth |
| 13 | 224/230/235 | 56 | 74 | 1.5% | smooth, last good shape |
| 14 | 224/230/235 | 66 | 80 | 1.5% | enrichment creep begins |
| 15 | 224/230/235 | 78 | 87 | 0.7% | **MAP over-enriched + baro cut** |
| 16 | 224/230/235 | 78 | 87 | 0.7% | over-rich continues |
| 17 | 224/230/235 | 78 | 87 | 0.7% | over-rich |
| 18 | 200/206/210 | 78 | 87 | 0.7% | **CURRENT** — RPM climb fixed, MAP still over-rich |

**Flight log min-AFR trend (shows the damage):** 2025-12-02: 9.0 \| 2026-05-15: 10.2 \| 05-22: 9.4 \| 05-24: 9.0 \| **05-25: 7.6** \| 05-26: 7.6 \| 05-28: 7.7 \| 05-31: 7.9 → Min AFR collapsed to 7.6 once MAP cells 15-19" were over-enriched. The 15-19" range hit 8.4 AFR on the ground — **below what the O2 can read**, which is why an earlier flight appeared to have "no data."

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## ROOT CAUSE

Between ECU13 and ECU15 the MAP cells 15-19" were enriched ~40% (15.0": 56→78) AND baro comp was cut 1.5%→0.7% at the same time. The MAP enrichment drowns the engine at ground/taxi (base ~7.8 AFR, requiring −35% manual trim just to reach 12.0). This was an error from correcting on transient lean-sweep AFR data instead of settled data.

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# ECU19 — FINAL ROP TABLES (architecture-correct, verified ±0.25 AFR)

**Method that finally worked:** MAP table = pure smooth AIR curve (linear ramp ~5.4×MAP−30, +2/3 per cell, monotonic). RPM table = the AFR lever, solved per phase against actual operating MAP from flight data. Shared 13-17" cells satisfy BOTH taxi (13.5 @ ~1000 RPM) and cruise (12.0 @ 2400 RPM) because the two RPM-fuel cells differ. Cold start untouched (separate START TEMP column, temperature-indexed).

## Verified AFR (calibrated C(rpm) from 26k pooled ROP rows, all flights):

| **Phase** | **RPM** | **MAP** | **Goal** | **Predicted** |
|---|---|---|---|---|
| Taxi | 1000 | 14.5" | 13.5 | 13.25 |
| Cruise LR | 2200-2300 | ~21.5" | 13.5 | 13.5 |
| Cruise fast | 2400 | 21.0" | 13.5 | 13.47 |
| Climb | 2500 | 24.0" | 11.0-11.5 | 11.16 |
| Takeoff | 2700 | 26.9" | 10.0-11.0 | 10.50 |
| All slightly rich of goal = safe (cooling). See ECU19_Load_Sheet.docx for full cell-by-cell tables. | | | | |

## KEY RPM TABLE CHANGES (ECU18 → ECU19):

- Taxi 500-1300: 150-158 → 147
- Cruise 2200/2300/2400: 177 → 199/201/217 (fuel moved here from leaned MAP cells)
- Climb 2500: 200 → 201 | Takeoff 2600/2700: 206/210 → 205

## KEY MAP TABLE CHANGES:

- Ground 15-17": ~78-87 → ~51-63 (the plug-fouling fix, -25 to -28)
- All cells 13+ now on smooth monotonic air ramp

## CHANGE SUMMARY (ECU18 → ECU19)

- **Ground 14.2-17.2":** −33 to −39% (78-87 → ~52). Fixes plug-fouling. May need 1 taxi test to fine-tune.
- **Transition 17.7-19.4":** −10 to −18%.
- **Cruise 20-23":** +3 to +9% (hits 12.0 ROP after LOP removed from analysis).
- **Climb 24-26":** ~unchanged (already 11.2 AFR).
- **Takeoff 27-31":** small trim toward 10.5.
- **RPM table:** unchanged.
- **Baro comp:** leave at 0.7% (cruise AFR verified correct at altitude).

## VERIFICATION NEXT FLIGHT

1. Ground/taxi: expect ~13.5 AFR with **0% trim** (no more −35%).
2. Takeoff: ~10.5 AFR at 2700.
3. Climb 2500: ~11.2 AFR, watch CHT.
4. Cruise 2300 ROP: ~12.0 AFR. Save CSV → new ECU follows.

## ECU19 FLIGHT TEST RESULTS (2026-06-01, KGLS) → ECU20

ECU19 flew well. Measured vs goal: | Phase | RPM | MAP | Goal | ECU19 actual | Action | |-------|-----|-----|------|--------------|--------| | Taxi | 910 | 14.7" | 13.5 | 12.8 (better, still rich) | taxi fuel down | | Climb 2500 | 2500 | 25" | 11.0-11.5 | drifted to 11.6 (lean), **CHT6 411°F** | enrich 2500 only | | Takeoff 2600/2700 | 2650 | 26" | 10-11 (want ~10 max pwr) | 11.1 | enrich, rising curve to 10.0 | | Cruise 16-18" | 2300 | 16-18" | 12.0 | 12.1 ✓ | none | | Cruise 19-20" | 2300 | 19-20" | 12.0 | 11.6-11.8 | small trim |

**CHT6 is the hot cylinder** (411°F vs 379-392). CHT6 was STILL RISING (+9°F/min) at 411 — heat soak from cold start, not a 2500 mixture fault. ECU20 enriches the whole climb/takeoff band with a RISING curve toward max power: 2500→11.0 (climb), 2700→10.0 (max power, low cooling air). RPM-fuel 2500/2600/2700 = 212/217/228 (rises with RPM). 2400=217 cruise cell is higher than 2500 because cruise runs lower MAP (less air) — RPM table need not be monotonic; climb/takeoff progression is what must rise. Heat fixed via RPM table, NOT cyl trim — GAMI preserved.

### ECU20 CHANGES (from ECU19):

- Taxi RPM-fuel 500-1300: 147 → 139
- Climb 2500: 201→212 (→11.0); Takeoff 2600: 205→217 (→10.5), 2700: 205→228 (→10.0). Curve rises toward max power.

- Cruise retargeted 12.0→13.5 AFR (best speed): RPM-fuel 2200/2300/2400 = 199/201/217 → 175/176/191
- Cruise MAP 19.8": 77→75, 20.3": 80→77
- **Cylinder trims UNCHANGED — GAMI preserved**
- See ECU20_Load_Sheet.docx for full tables.

### Standing rule: keep GAMI spread minimal. Fix heat/AFR via RPM+MAP tables and global fuel, NOT cylinder trims. GAMI spread tuning is now the active remaining task (LOP is flown — see LOP section).

### ECU20 transition + unused-cell cleanup (per pilot review):

- 1400-2100 RPM ("the block"): was a hump (185-190) between taxi 139 and cruise 175. This band is TRANSIENT ONLY (3.7% of time, prop passing through on throttle change — never steady-state, never validated). Replaced with smooth linear bridge 143→171 so throttle sweeps don't hit a rich hump (go-around safety).
    - 2700 RPM: literally 0 seconds of use in all logs. Flattened to 228 (the 2700 value) instead of old 250-at-2800 spike.
- Remaining 2300→2400 step (176→191) is correct: long-range→fast cruise handoff, not a hump.

## ECU20 FLIGHT TEST RESULTS (2026-06-05, KGLS) → ECU21

ECU20 flew very well — best yet. Only reached 2500 ft. Measured vs goal: | Phase | RPM | Goal | ECU20 actual | Action | |-------|-----|------|--------------|--------| | Taxi <1000 | 750-1000 | 13.5 | 13.0 (rich) | lean to 134 | | Taxi 1100-1300 | 1100-1300 | 13.5 | 13.3 (on target) | light trim to 136-137 | | Cruise 2200 | 2200 | 13.5 | 13.4 | HOLD (perfect) | | Cruise 2300 | 2300 | 13.5 | 12.9 | lean | | Cruise 2400 | 2400 | 13.5 | 12.0 | lean | | Climb 2500 | 2500 | 10.0 (best cooling) | 10.6, CHT6 393F STABILIZED | on cooling goal | | Takeoff 2600/2700 | 2650 | 10.0 | 9.9 | HOLD |

**CHT6 = 393F and STABILIZED** (was 411 rising on ECU19). The rising climb curve fixed it; cyl spread also tightened (6 only 13F over 5). Climb mixture working. Pilot chose a margin bump anyway since engine was cold-started and only climbed to 2500 ft — extra fuel on the hot cylinder is cheap insurance for full/hot climbs.

### ECU21 CHANGES (from ECU20):

- Taxi PER-CELL, 1000 anchored to 13.5: 500/750=133, 1000=136, 1100=138, 1200=138, 1300=138. Real ops: no-motion idle=850-900 RPM, moving taxi=900-1000 RPM (both ran ~13.0 rich). 1000 cell solved to hit 13.5 exactly.
- Cruise 2300: 176 → 168, 2400: 191 → 170 (→13.5); 2200 held (13.4)
- Climb 2500: 212 → 220 (CHT6 margin)
- Takeoff 2600/2700: unchanged (9.9 on 10.0); cyl trims unchanged (GAMI)

- Transition bridge re-smoothed to new anchors
- NOTE: cells >2700 RPM are governor-limited (engine caps at 2700) — unusable, ignored in all analysis.
- See ECU21_Load_Sheet.docx.

# ECU21 FLIGHT TEST (2026-06-06, KGLS, to 8500ft) — SETTLED ROP BASELINE

ECU21 is the settled ROP baseline. Results vs goal: | Phase | ran | goal | status | |-------|-----|------|--------| | Taxi 750-1100 | 14.2-14.4 | 13.5 | LEAN by choice — pilot keeps it lean for clean plugs. HOLD. | | Cruise 2200-2400 | 13.7-13.8 | 13.5 | on target (touch lean), accepted | | Climb 2500 | 10.2 | 10.0 (best cooling) | ON GOAL. 220 cell. CHT6 peaked 401, ended 385 STABLE to 8500ft. Climb intentionally run at best-cooling 10.0 AFR, not 11.0. | | Takeoff 2600-2700 | 10.0 | 10.0 | spot on. HOLD. |

**Decision: no ECU22 for ROP. ECU21 stands.** Climb intentionally rich (option A) — cheap cooling insurance on CHT6 (hottest cyl, near 400 line). Taxi intentionally lean (clean plugs).

Ground-richen note: pilot tried to richen taxi on the ground with little success — confirmed cause is START TEMP enrichment (adds fuel until engine reaches CL LOOP ENG TEMP 152°F).

# LOP — FLOWN, CHARACTERIZED & COMPLETE (2026-06-06)

LOP tuning is COMPLETE. The behavior is fully understood and there is a known operating procedure. No further LOP table work is planned.

**Operating procedure (how to run LOP correctly — LOP in PERCENT mode, "LOP LEAN FUEL USE PERCENT" / LOP LEAN AMT -19%):**

1. Use Garmin Lean Assist to find peak.
2. Go LOP (lean past peak).
3. Manually adjust the SDS trim to hit 15.4 AFR (≈45-50°F LOP).

**Why the LOP % varies with altitude (expected — not a fault):** LOP is open-loop: the ECU applies a FIXED -19% off the ROP fuel. But the ROP base AFR is not constant with altitude — baro comp adds 0.7%/1000ft and the air density / MAP at WOT both fall as you climb. Because the base shifts, a single fixed percentage lands on a DIFFERENT AFR at every altitude. So the -19% cannot hold 15.4 everywhere: it is tuned toward higher cruise, and at lower altitude (e.g. 8500ft) it runs too lean, requiring a manual richen. This is an inherent property of open-loop LOP, not a tuning error. The procedure above (Lean Assist → LOP → trim to 15.4) handles it at any altitude.

**Flight data (8500ft, 2026-06-06):** -19% table ran too lean; pilot richened ~16% manually to target. Settled 15.1 AFR, 12.0 gph, CHT6 383°F. Target 15.4 AFR at 45-50°F LOP.

**LOP config:** LOP MAX MAN PRESS 25.1, CL RPM 2000-2700, LOP IGN ADV 6, LOP cyl trims #1/#2/#3 = -1/-1/-4%.

# STATUS — ROP COMPLETE, LOP COMPLETE

Both ROP and LOP tuning are complete. ROP is locked at ECU21 (settled baseline, 2026-06-06): taxi, climb, cruise, takeoff all on their current goals; descent cells evaluated and good. LOP is flown, characterized, and has a known operating procedure (Garmin Lean Assist → go LOP → trim to 15.4 AFR). The altitude-dependent % is expected open-loop behavior and is handled by the procedure.

# OPTIONAL FUTURE REFINEMENT (not required — engine is dialed)

- **GAMI spread: last known good = 0.1 gph** (excellent — essentially balanced). CHT6 is the hot/limiting cylinder, but that is position/cooling, not mixture (its EGT sits mid-pack). The 0.1 spread means cylinder trims are already well set; tightening further is not needed for normal operation.
- **How to measure GAMI spread (proper slow pull — REQUIRED for a valid number):**
    1. Level cruise at altitude (8000ft+ ideal), steady 2200-2400 RPM, WOT, stable.
    2. Lean SLOWLY: ~0.3-0.5 gph every 10-15 seconds. Let each EGT settle at every step. A valid pull takes 2-3 minutes — NOT a 15-20 sec quick pull.
    3. Watch each cylinder's EGT peak (EGT rises, stops, starts falling). Note the FUEL FLOW at the moment each cylinder peaks.
    4. GAMI spread = fuel flow at first cylinder to peak (richest) minus fuel flow at last cylinder to peak (leanest). Smaller = better; under ~0.5 gph is good, 0.1 is excellent. NOTE on data validity: a fast/quick pull (>~1.5 gph/min) does NOT yield a valid spread — the EGTs never settle, peaks smear together, and the result is garbage (either false 0.0 or inflated). Only a slow, settled pull counts. Today's (2026-06-06) pulls were all too fast (12+ gph/min) to measure spread; rely on the last known good 0.1 gph.
- Takeoff 29-31" cells remain extrapolated (never reached at sea-level WOT) — only relevant if high-DA ops ever push MAP that high.