Air-Fuel Ratio Measurement using Ceramic Sensors

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AFR: Definition

Two Definitions Used but Several Values Calculated

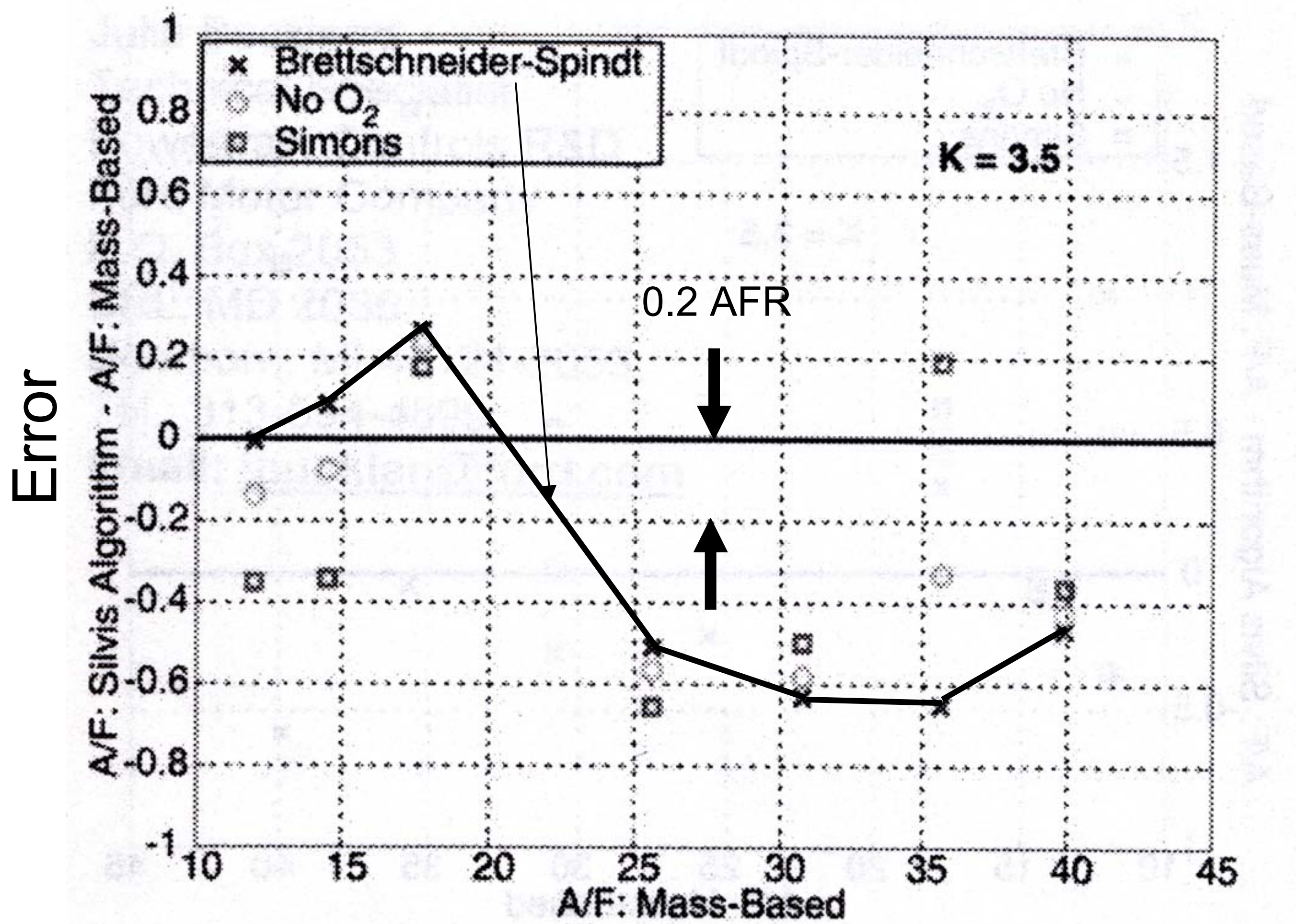
1. AFR = Mass Airflow/Mass Fuelflow
   - A direct measurement
   - Conservation of mass is compelling

2. Gas Bench Calculated AFR (C,H,O,N balances)
   - An indirect measurement
   - What calculation (Brettschneider, FAFN,…)?
   - What assumptions?
   - What bench?

Recall: $\lambda = AFR/AFR_{stoichiometric}$

$AFR_{stoichiometric}$ calculated from fuel composition

Ford Data (SAE Paper 2003-01-0566)

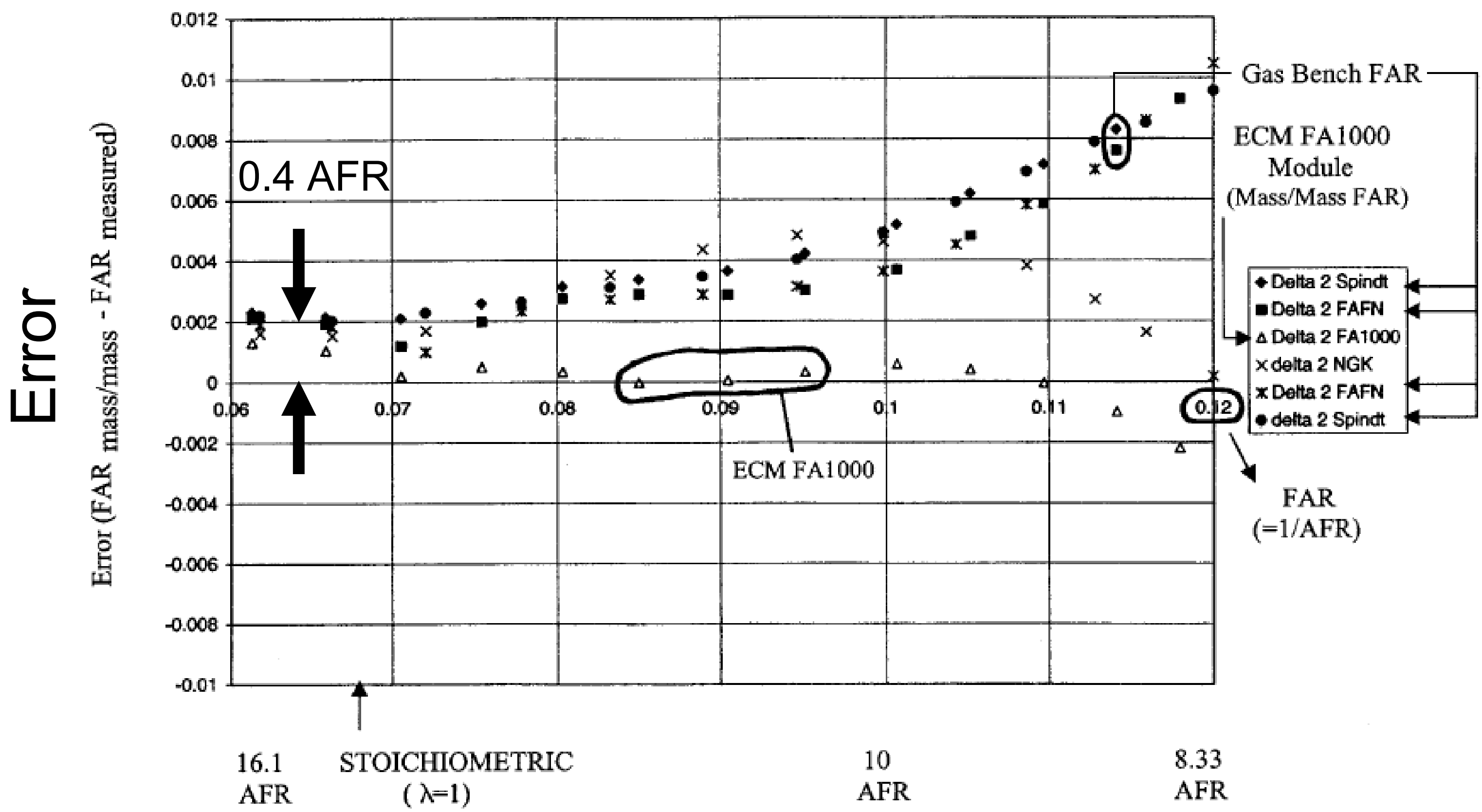


What do you want to Report: AFR_{mass} or AFR_{bench}?

- AFR_{mass} is historically what people wanted to match. It can be verified by measurements of fuel and air mass flowrates.

- AFR_{bench} should compare to gas bench methods (i.e. C, H, O, N balance techniques). But many details (ex. formula, equilibrium assumptions, HC assumptions) result in different calculated AFR numbers. Which one do you want to match?

One Car Company's Data



My Point Here

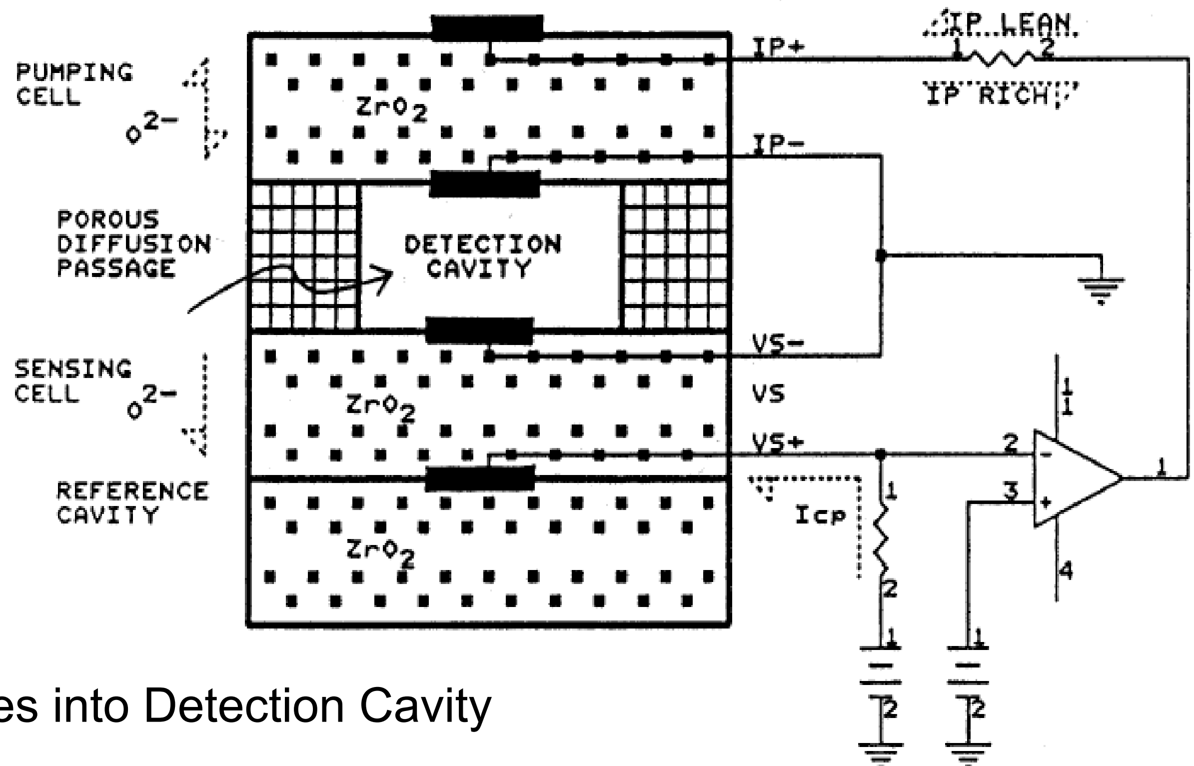
- The AFR meter is going to output an AFR number. Done right, it will be a consistent and repeatable number. We can consistently match anything. What do you want to match?
- AFR measured by mass/mass methods will generally result in the same number no matter where and who does it. It’s a relatively simple measurement.
- AFR measured by bench methods will vary from organization to organization and each one will swear that their method is the correct one. The differences are in the details and there are a lot of details.

How the AFR Sensor Works

Exhaust

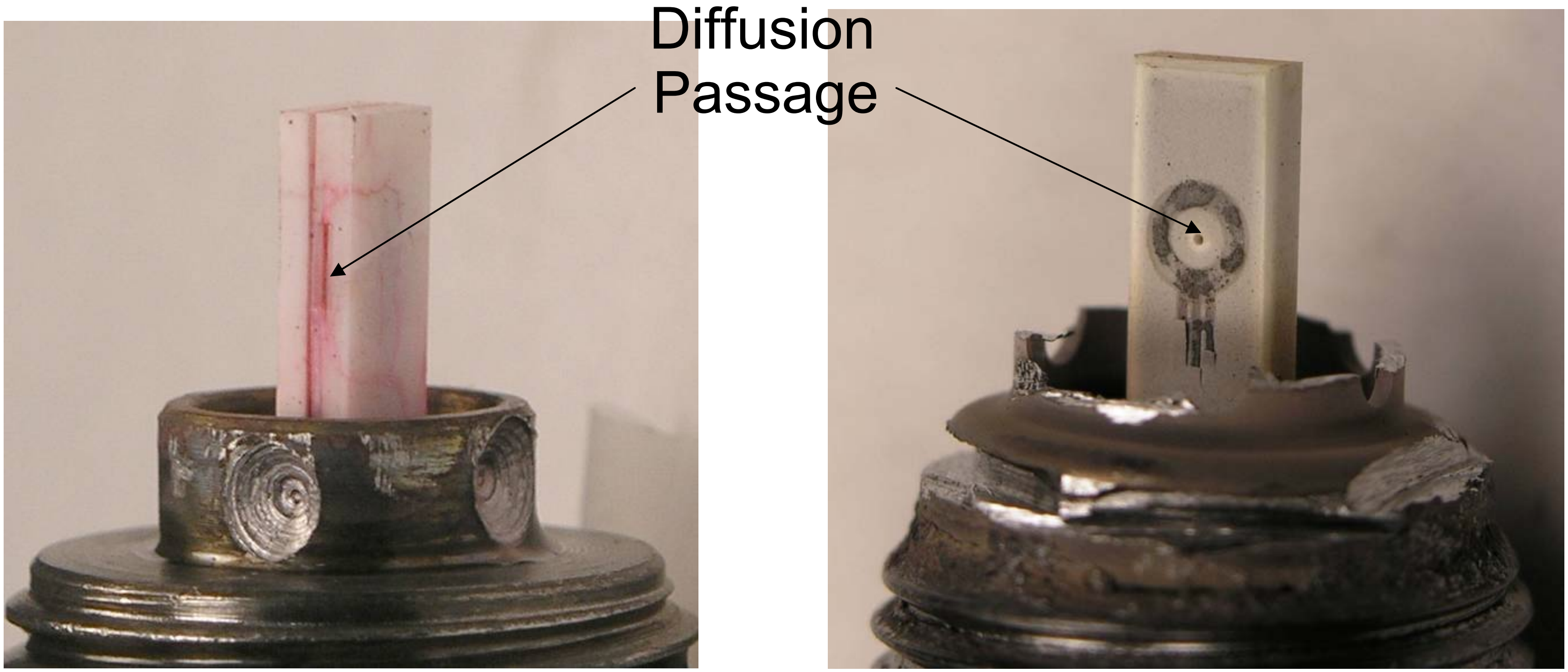
Lean: O_2

Rich: CO, H_2, HC



- Exhaust diffuses into Detection Cavity
- O_2 pumped into and out of Cavity to maintain equilibrium λ=1 in cavity as detected by the Vs voltage. Equilibrium λ=1 means negligible O_2, CO, H_2, and HC.
- So for lean mixtures, you are pumping O_2 out and for rich mixtures you are pumping O_2 in to burn the CO, H_2, HC. Pumping measured by Ip.

NTK UEGO **BOSCH LSU**



Important AFR Sensor Assumptions

- By the time exhaust has diffused into the cavity, it is at equilibrium conditions.
  i.e. Lean mixtures contain negligible CO, H2, HC, but there is O2
  Rich mixtures contain negligible O2, but there is CO, H2, HC

- Therefore, the sensor's pumping current Ip is only proportional to equilibrium O2 in the exhaust when lean and only proportional to equilibrium CO, H2, HC in the exhaust when rich.

  For lean mixtures if you can infer an %O2 based on the sensor's pumping current, you can back-calculate the AFR.

  For rich mixtures, if you infer a %CO, %H2, %HC based on the sensor's pumping current, you can back-calculate the AFR.

  Mathematics to derive AFR from Ip are similar to a ***specific*** gas bench calculation. Various tweeks will make it match anything. So you can tweek it to match mass/mass and you can tweek it to match any bench. Generally tweeks are of the form: $\lambda = \lambda_{calc} + f(\lambda)$. ECM delta table = $f(\lambda)$.

AFR Sensor Calculation

(Lean Calculation, No Oxygen or Nitrogen in Fuel, Equilibrium at 750 °C, 1 Atm.)

$$C_1H_m + \lambda(1 + m/4)(O_2 + 3.773N_2) \rightarrow CO_2 + aO_2 + bH_2O + cN_2$$

Conservation of O2: $\lambda\ (1 + m/4) = 1 + a + b/2$
Conservation of H: $m = 2b$
Conservation of N2: $\lambda\ (1 + m/4)\ 3.773 = c$

Xo2 = %O2/100 = a / (1 + a + b + c), Note: “Wet” %O2 (water “b” in denominator).

After some math: **λ = (z + Xo2 (m/4)) / (z (1 – 4.773 Xo2))** , where z = 1 + (m/4), Xo2 = %O2/100

How to get Xo2?: Ip (sensor current) = %O2 x [mA/%O2], where [mA/%O2] is the gain of the sensor

Rich calculation more complex: No O2. CO, H2, and HC included.
Water-gas equilibrium equation.
Need CO, H2, and HC gains of sensor: Ip = -(%H2[mA/%H2] + %CO[mA/%CO] + %HC[mA/%HC])

Let's Put in Some Humidity

(Lean Calculation, No Oxygen or Nitrogen in Fuel, Equilibrium at 750 °C, 1 Atm.)

$$C_1H_m + \lambda(1 + 1.85/4)(O_2 + 3.773N_2) + d\ H_2O \rightarrow CO_2 + aO_2 + bH_2O + cN_2$$

Conservation of O2: $\lambda\ (1 + m/4) + d/2 = 1 + a + b/2$
Conservation of H: $m + 2d = 2b$
Conservation of N2: $\lambda\ (1 + m/4)\ 3.773 = c$

Xo2 = %O2/100 = $a / (1 + a + b + c)$

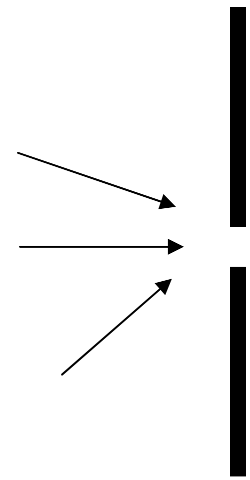
After some math: Another equation. Actually two equations (AFR(dry), AFR(wet)).

Ex.: Using formula on previous page, with m = 1.85, true λ = 1.2 (AFR = 17.47), and air at 70 °F, 100% humidity, you would calculate λ = 1.194 (AFR = 17.39). In other words: an error of less than 0.1 AFR.

Effect of humidity is to reduce %O2 in exhaust.

How to Get:
[mA/%O2], [mA/CO], [mA/H2], [mA/HC]?

1. Put known concentration of %O2 (or CO, H2, HC) outside sensor.



2. Measure resultant Ip from sensor as O2 (or CO, H2, HC) diffuses into sensor. Sensor will reduce the %s of these species to negligible number.

- Ip is linear with O2, CO, H2, or HC and there is a negligible offset. Therefore, the greater the value of O2 (or CO, H2, HC) used, the greater the accuracy. i.e. +-0.1%O2 at 20% O2 means +-0.05 at 10%.
- Due to sensor electrode characteristics, there is a threshold effect of H2O on these gains. You will need a little “known” H2O in your known concentrations. i.e. Don’t use tanks of pure air. There is no water.

The Case for Calibrating with Air

- Using air to determine [mA/%O2] is good for 3 reasons:
    1. Extremely accurately known (20.945 – humidity)
    2. Already contains H_2O
    3. Cheap
- Little known fact:

  [mA/%X]/[mA/%O2] = Constant.

  This means that you do not have to “cal lean” then “cal rich”. They scale. Diffusion passage is very large relative to molecular size. If a bigger hole lets in twice as much O_2, it will let in twice as much CO, H_2, and HC.

In other words…

- Take any one of these NTK, Bosch, or Delphi sensors, calibrate it in air, and run it rich and lean in an engine and you're going to get very similar AFR numbers.[1]

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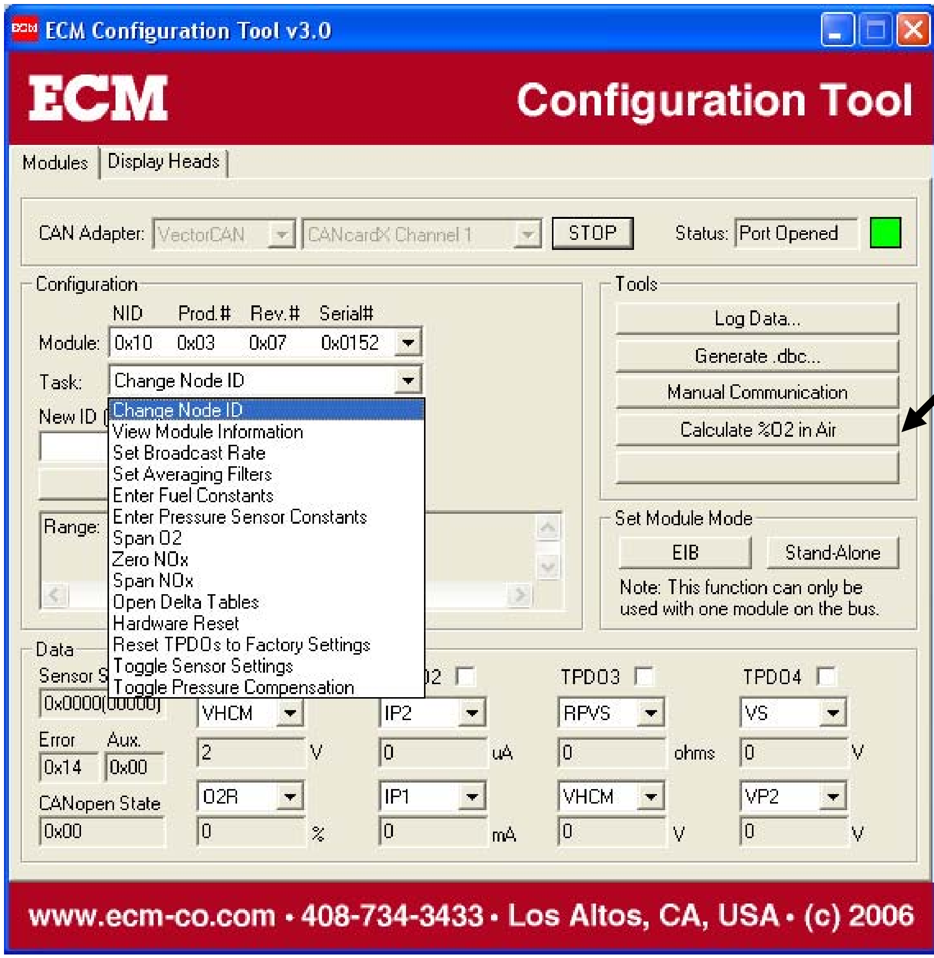
[1] ±0.1 AFR (less than ±0.01 λ) if using an ECM product.

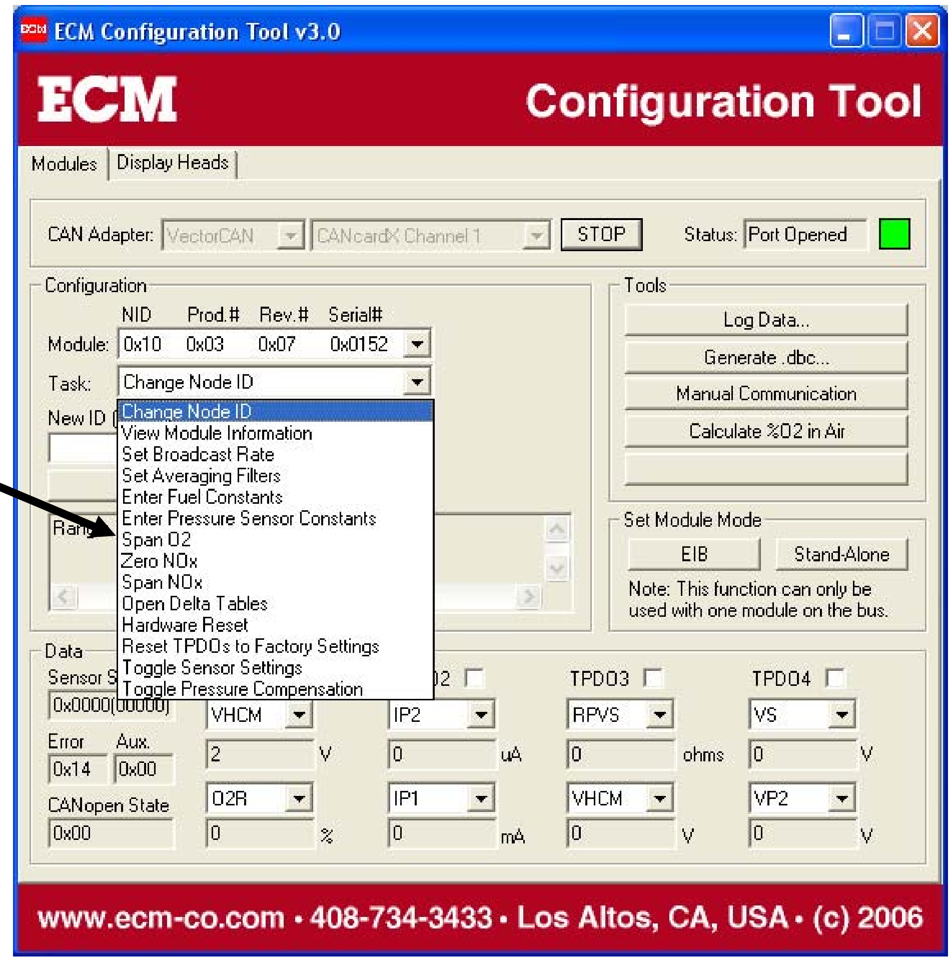
Easy to Calculate %O2 in Air



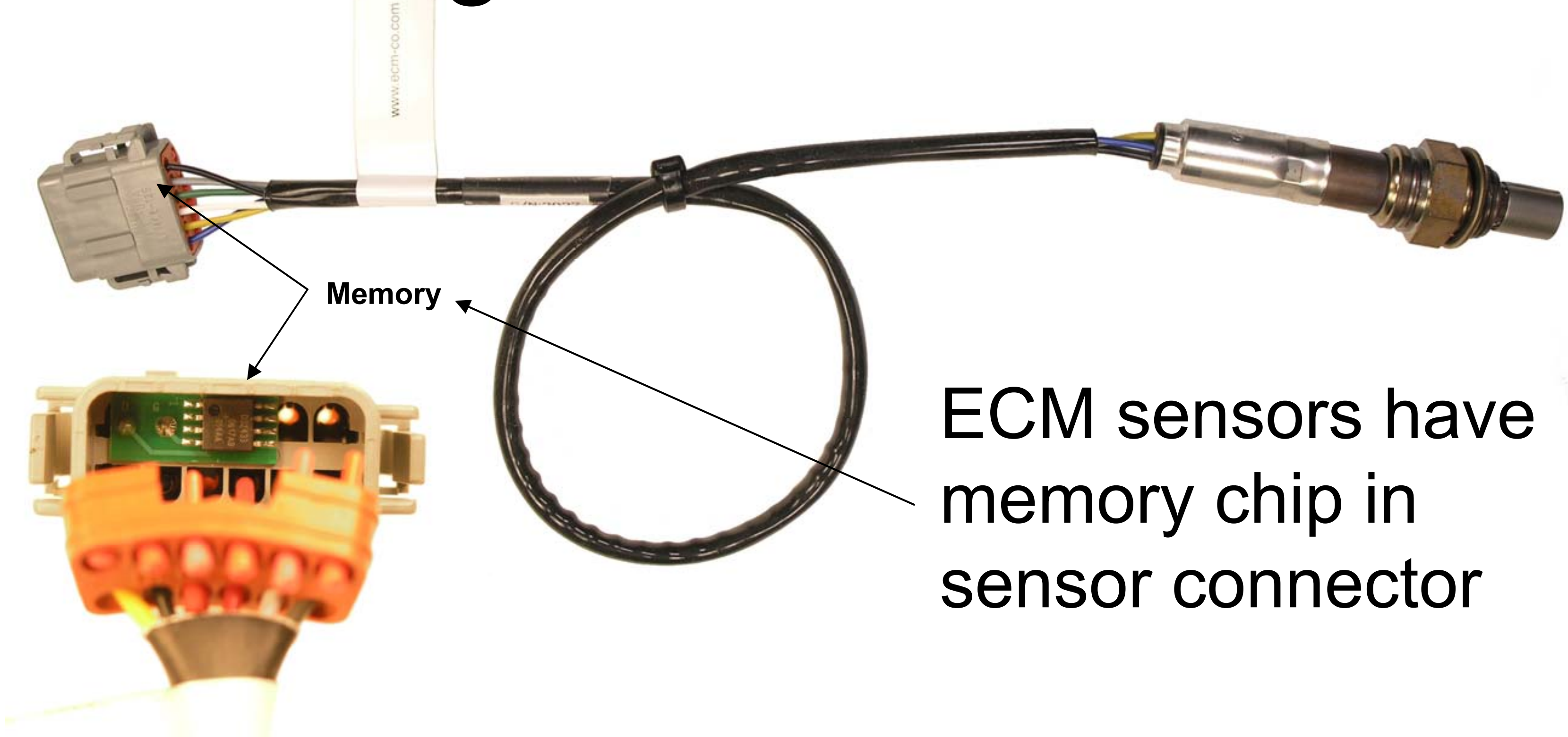
Does humidity calculation for you!

Easy to Calibrate

One click and sensor is calibrated. Now put back in stock for use.



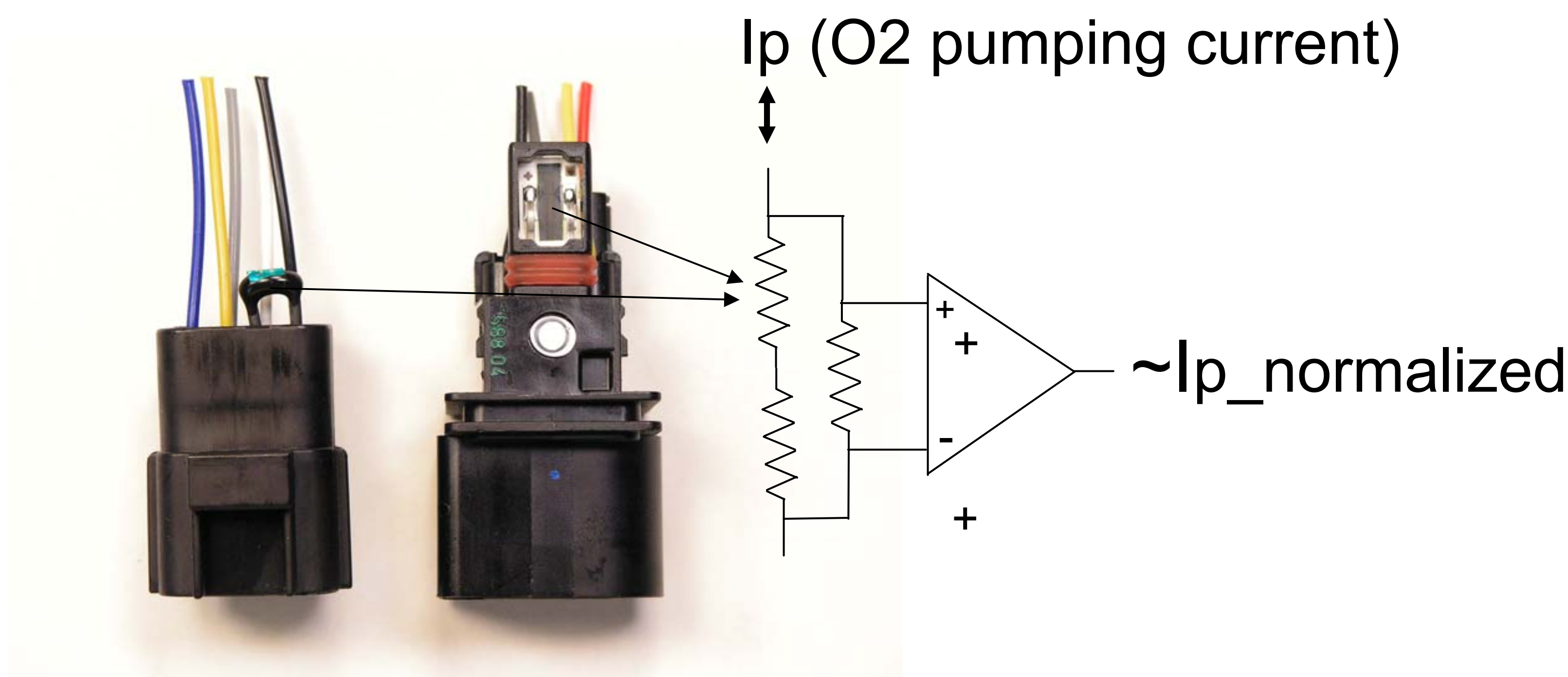
ECM Programmable Calibration



ECM sensors have memory chip in sensor connector

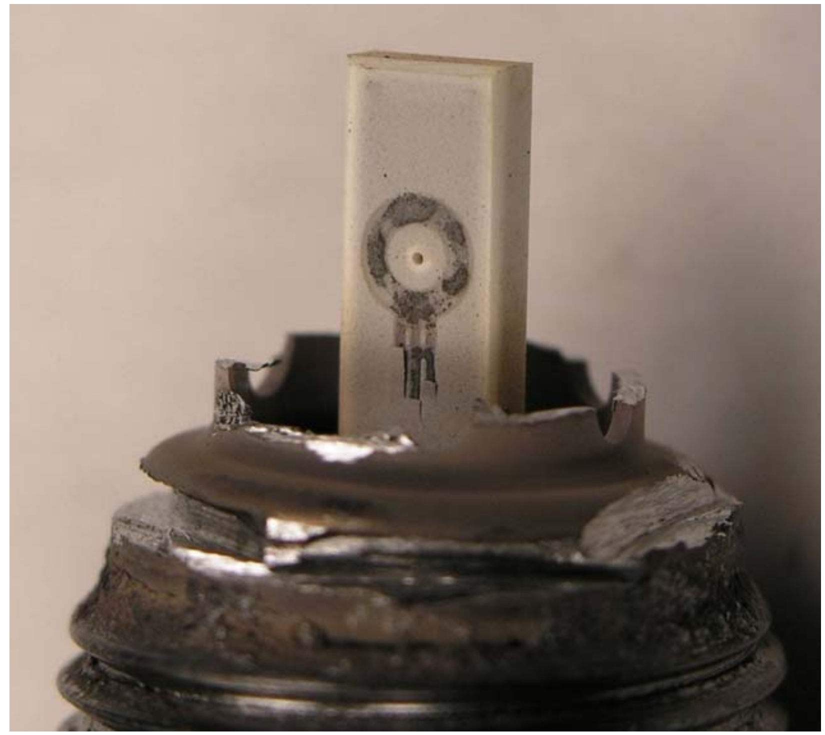
- Memory chip stores identification, calibration, and pressure compensation information
- Memory allows uniform company-wide calibration to be performed in central location
- Extends usable life (i.e. accuracy) of sensor through recalibration

Versus Non-Programmable Calibration



- Resistor trimmed to scale Ip onto “normalized Ip curve”. This compensates for diffusion passage size of that sensor when new.
- Resistor incorrect when sensor ages and results in drift

Does Calibration Drift?



Yes, little holes plug when in the exhaust of an engine.

How the AFR Meter Works

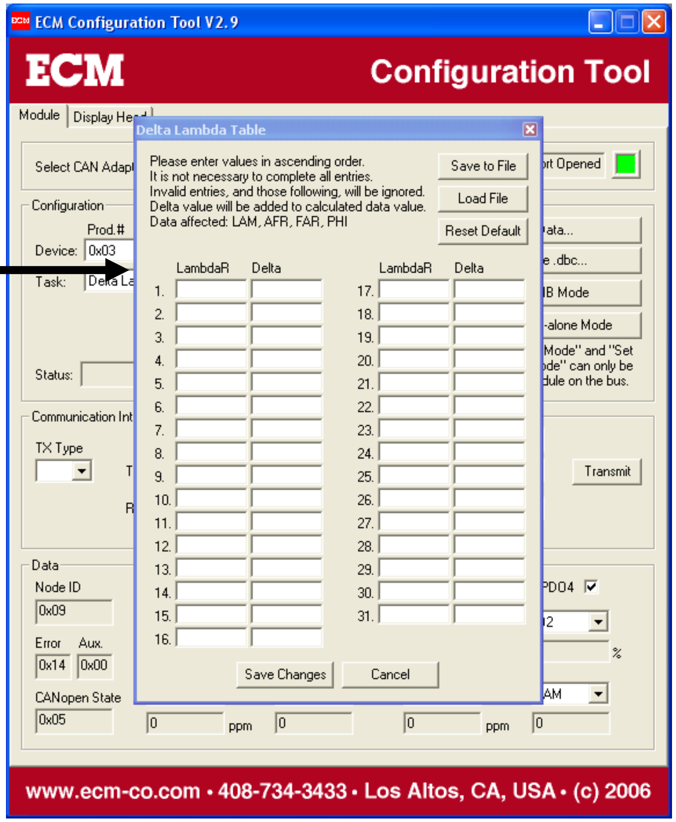
$$\lambda \sim Ip \times [\%O2/mA] \times [\lambda(\%O2)] + f(\lambda)$$

- AFR meter electronics measures Ip. You test ability of electronics to do this using ECM Sensor Simulator.
- Calibration of sensor tells you [%O2/mA] and through association [%X/mA]
- The fundamental sensor calculations
- Optional “tweek”. Match anything. With no tweek, we match mass/mass.
- Note that the AFR meter operation is verifiable. You can check the ability of the electronics to measure Ip using the sensor simulator, you can calibrate the sensor, and you can match AFRmass or AFRbench of any bench.

Optional Tweek: Match Anything

Delta Table

f(λ)



But…

What is the biggest source of error when using ceramic sensors for AFR determination?

The Dirty Secret of AFR Sensors: Pressure Sensitivity

Effect of 35 kPa (5 psi, i.e. "nothing") change in exhaust pressure:

1. Error of 0.02 Lambda at λ = 0.68 (cold start or catalyst cooling)
2. Error of 0.01 Lambda at λ = 0.84 (maximum power)
3. Negligible error at λ = 1 (stoichiometric)
4. Error of 0.1 Lambda at λ = 1.7 (lean-burn port injection)
5. Error of 0.6 Lambda at λ = 3 (gasoline direct injection or diesel)
6. Error of 4 Lambda at λ = 6 (light load diesel)

Solution to Pressure Problem

- Use Pressure Compensation (P-comp) for non $\lambda = 1$ operation, especially lean-burn and diesel applications.

Recommendations

- Standardized location (Before catalyst (i.e. engine-out). Minimum distance from exhaust valve and minimum distance from exit of exhaust)
- Standardized calibration (air minus humidity, time)
- Standardized calculation and delta table to match mass/mass or a specific bench
- Pressure Compensation (LambdaCAN + Pcomp)
- Optional: Use most durable sensor (NTK 6mA)
- Optional: Do humidity compensation (ECM BaroCAN)
- Optional: Set maximum hours of sensor use

Types of Ceramic Exhaust Sensors

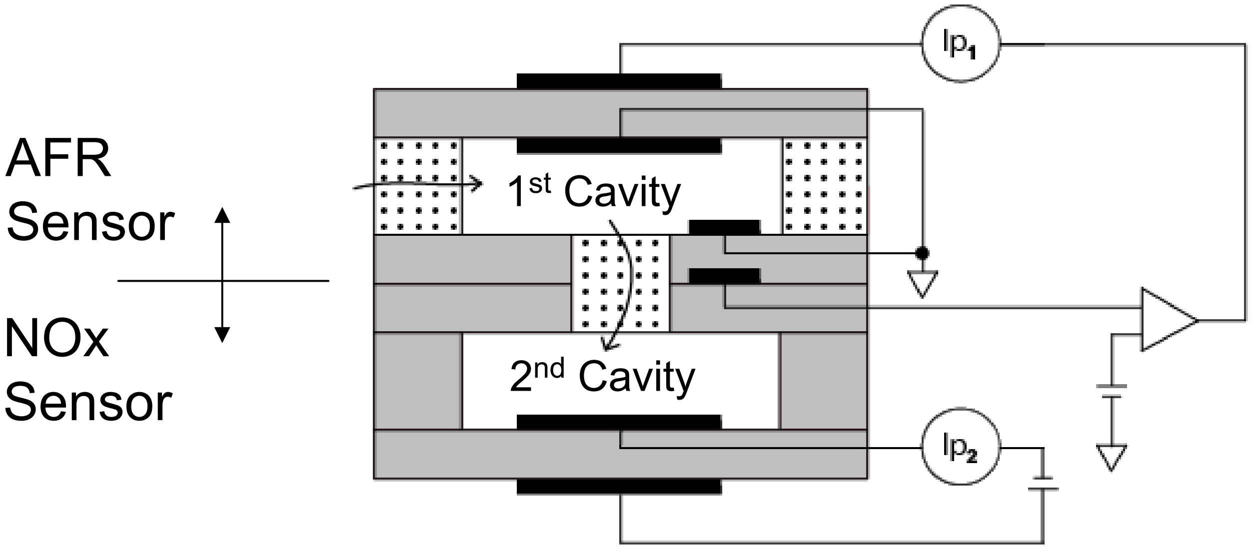
- EGO/HEGO: λ=1, Nernst Type,1~4 Wire

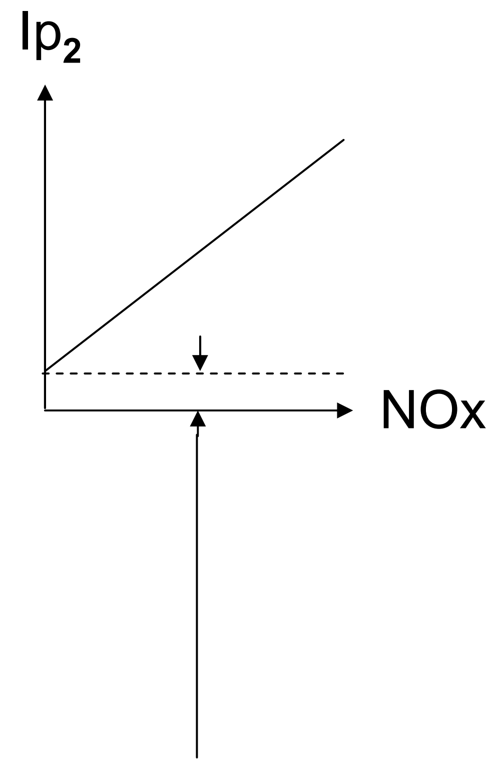
- AFR/Lambda/UEGO: Wideband λ, 5 or 6 Wire
- NOx/O2: 6 or 8 Wire
- NH3: 6 Wire

In development:

Soot, CO, HC

NOx Sensor Operation





- 1st Cavity: Control to $\lambda=1$
- 2nd Cavity: Strip oxygen from NOx and "$\lambda=1$" O_2

The Scoop on NOx Sensors

- ±15ppm accuracy[1]
- Sensitivity to NH_3 (same for bench CLA)
- Lean okay. Rich use “less charted”.
- Thermal sensitivities (exh pipe, gas)

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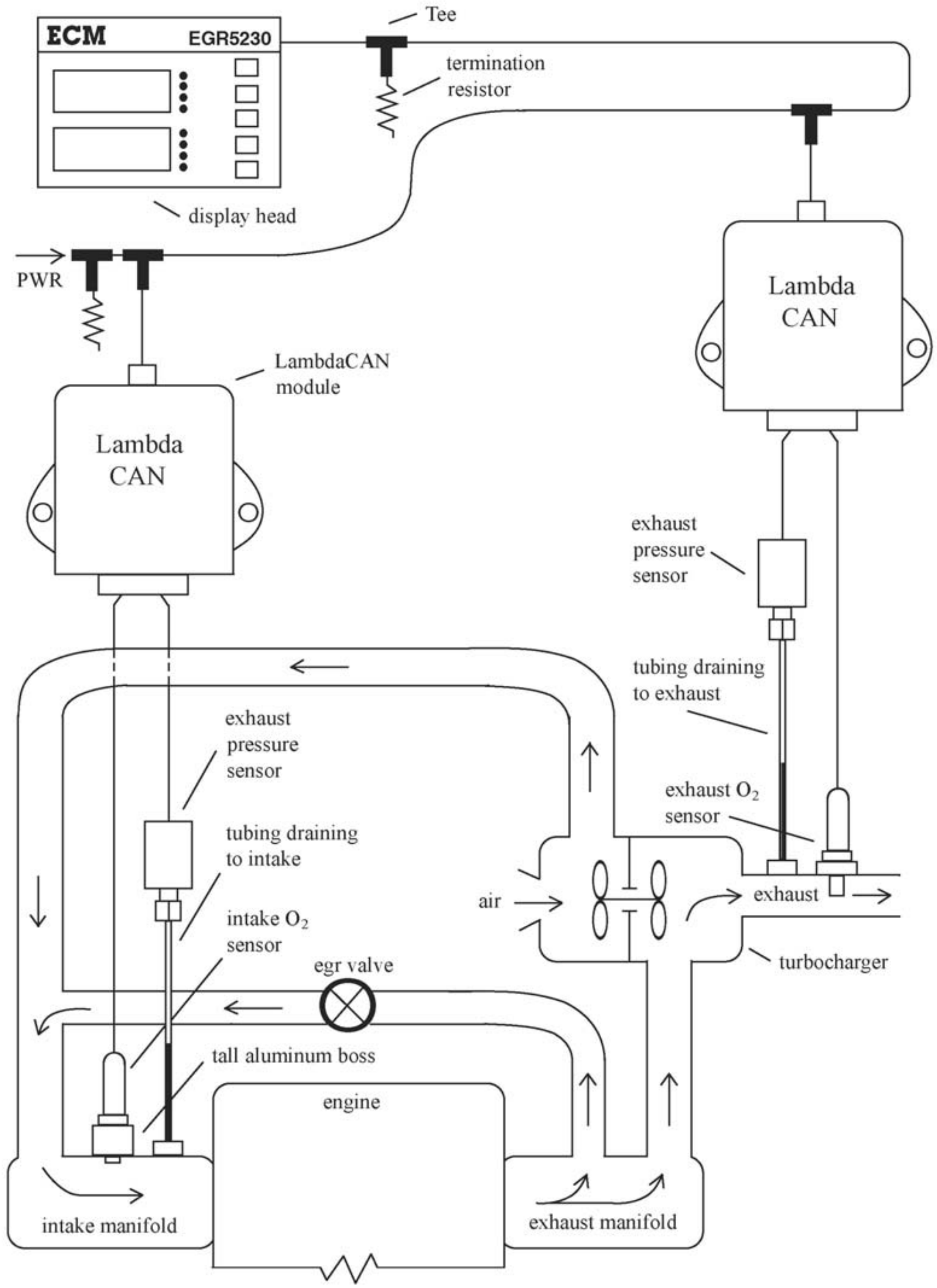
[1] For new “Type G” NOx Systems (Q3/2008)

EGR

- Fast
- Portable



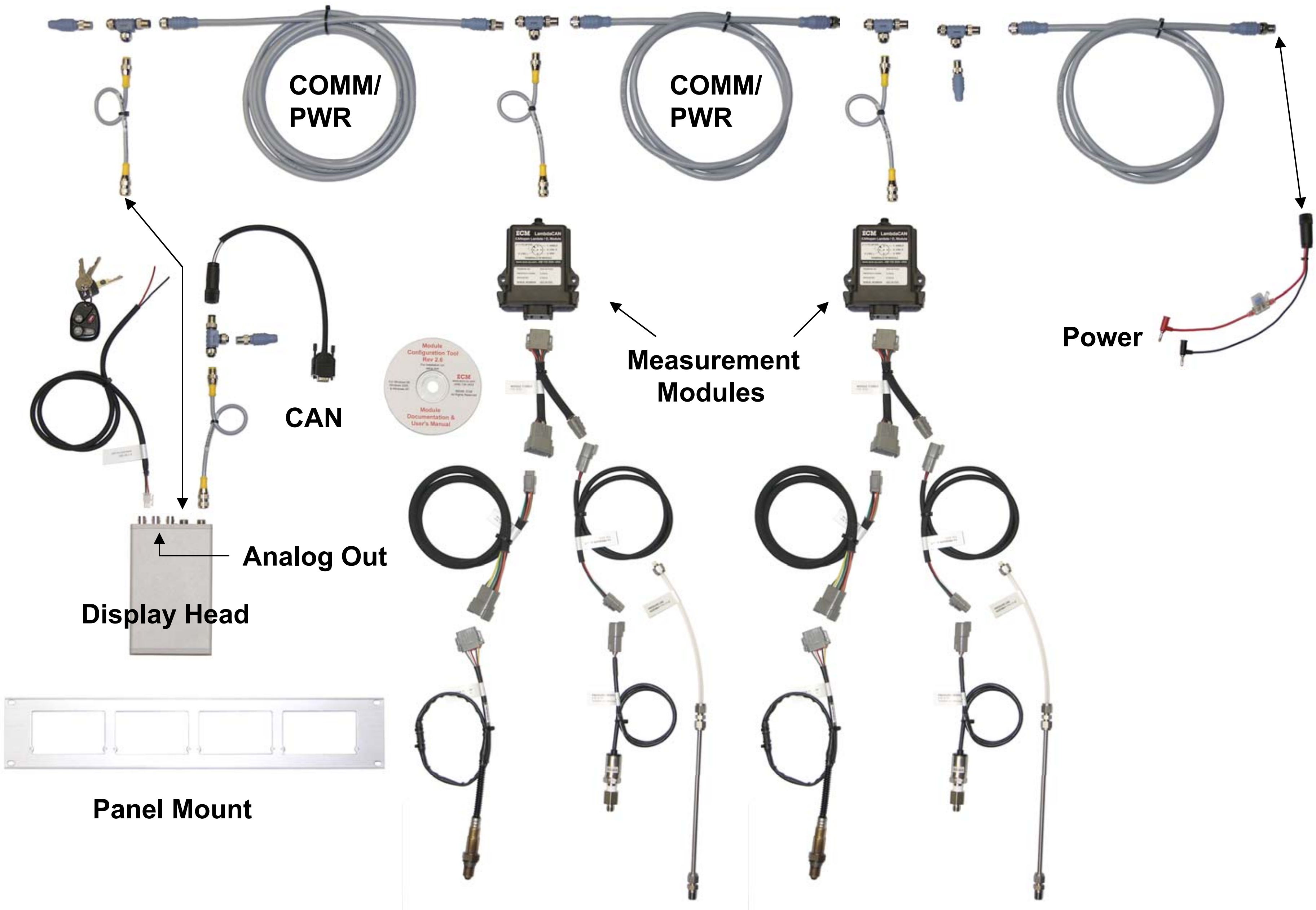
New Instruments from ECM

6 Analog Out

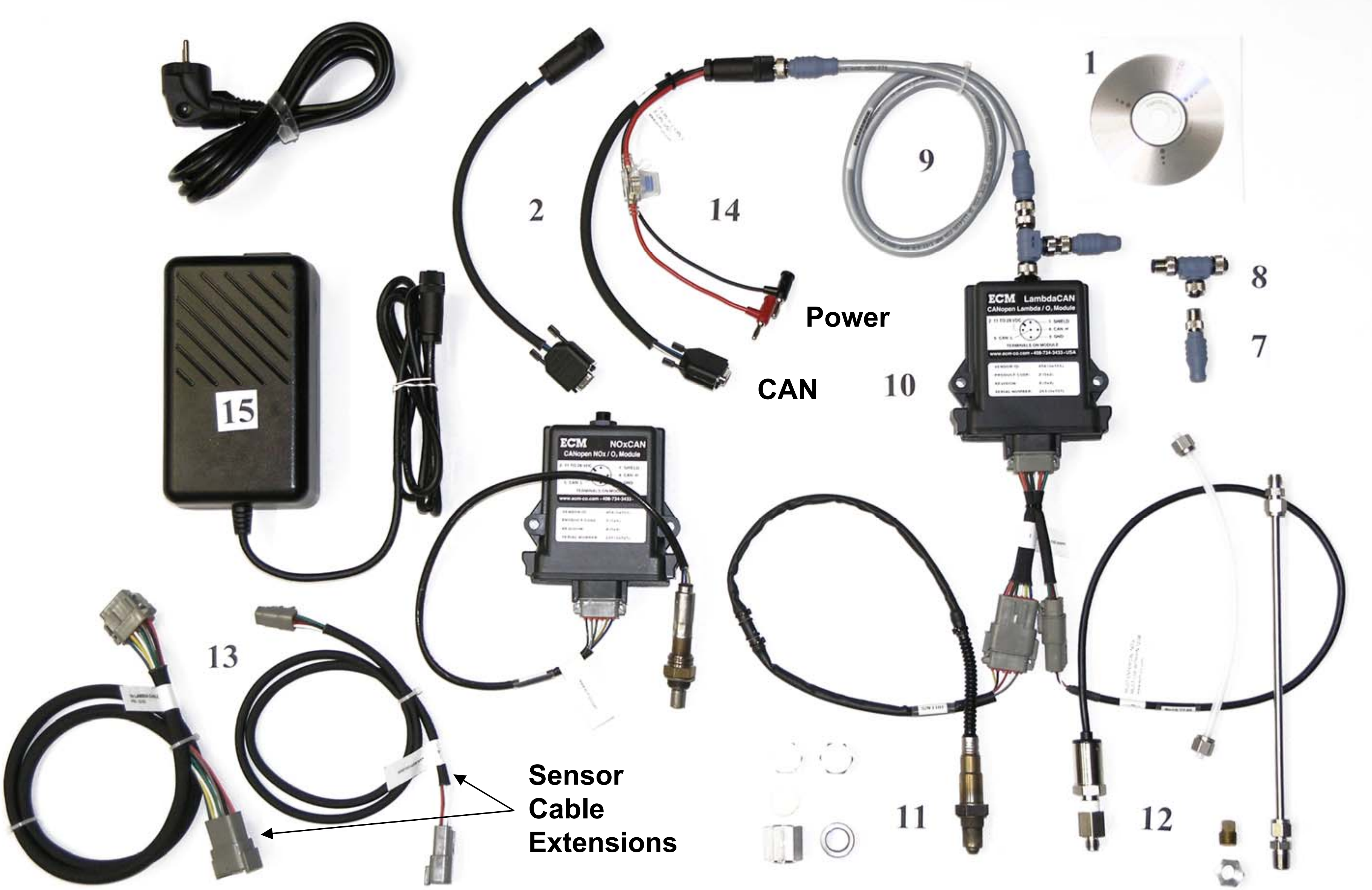
CAN

RS232

EGR 5210, Lambda 5220, EGR 5230 Analyzers



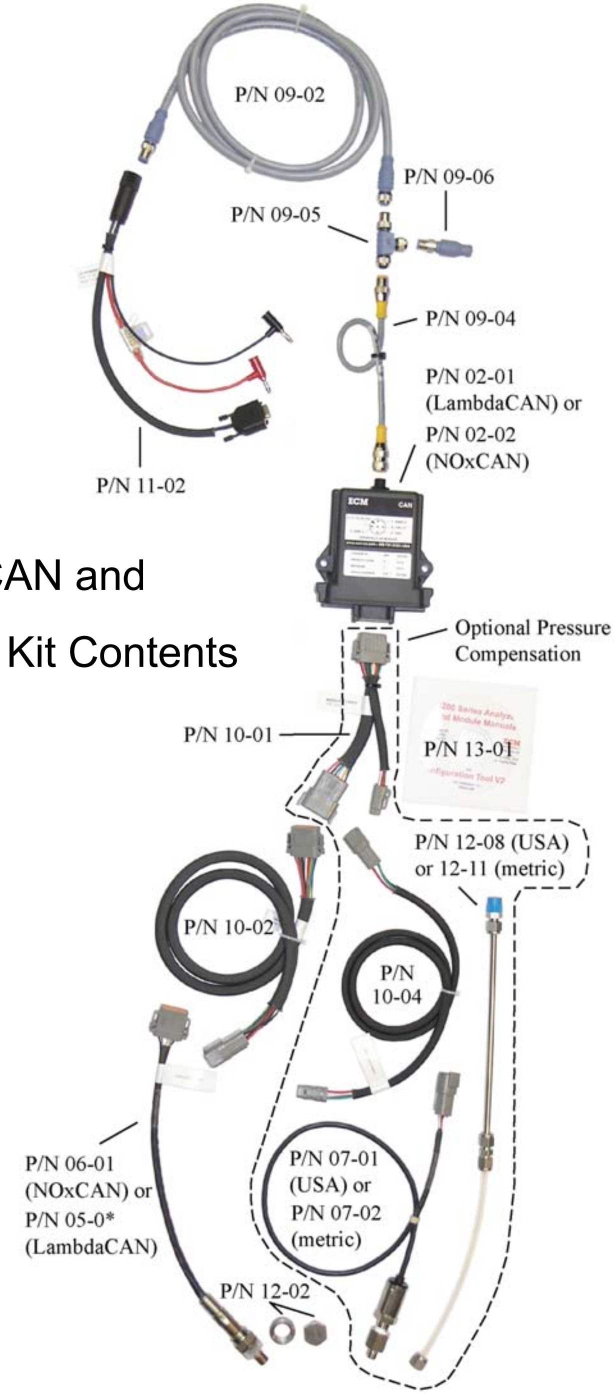
LambdaCAN and NOxCAN Systems



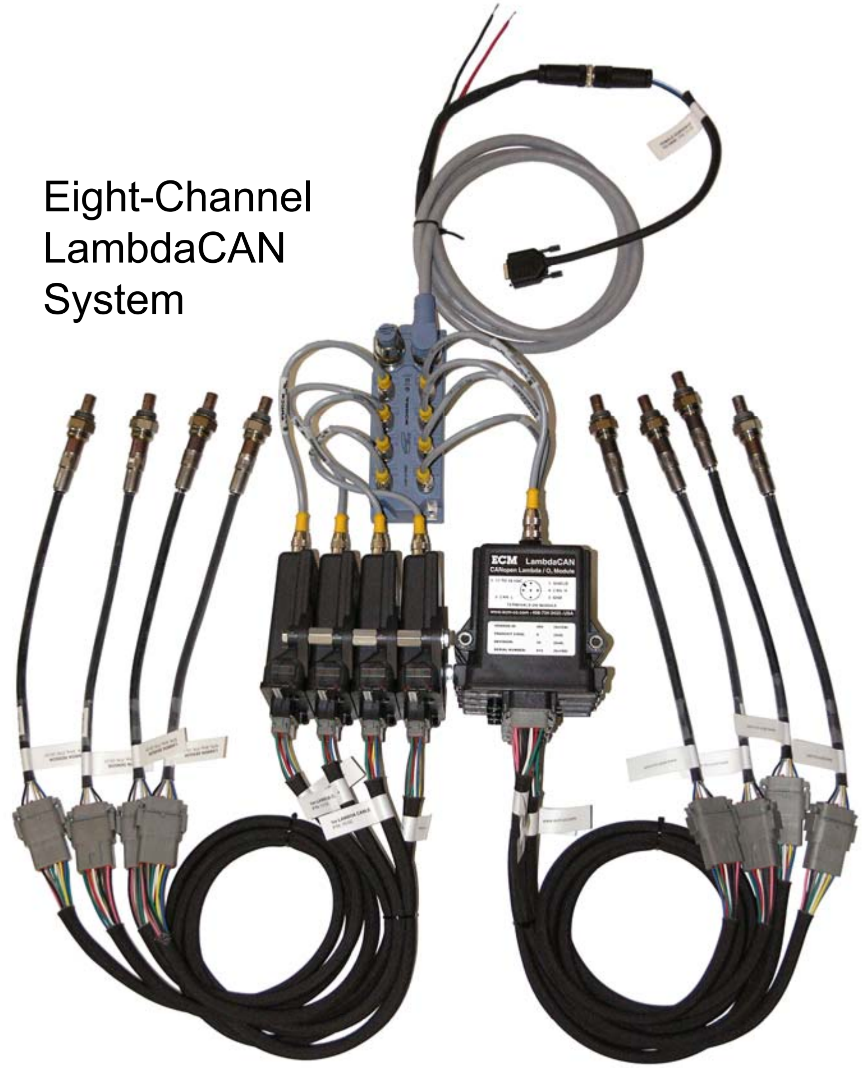
Easily build Sophisticated Lambda and NOx Measurement Systems

Example: 5 Channel (3 LambdaCAN, 2 NOxCAN) Pressure Compensated System

LambdaCAN and NOxCAN Kit Contents



Eight-Channel LambdaCAN System



Dashboard Display for CAN Networks

Prototype Multi-Channel Lambda “Attack Cart” with Integral Sampling Pump

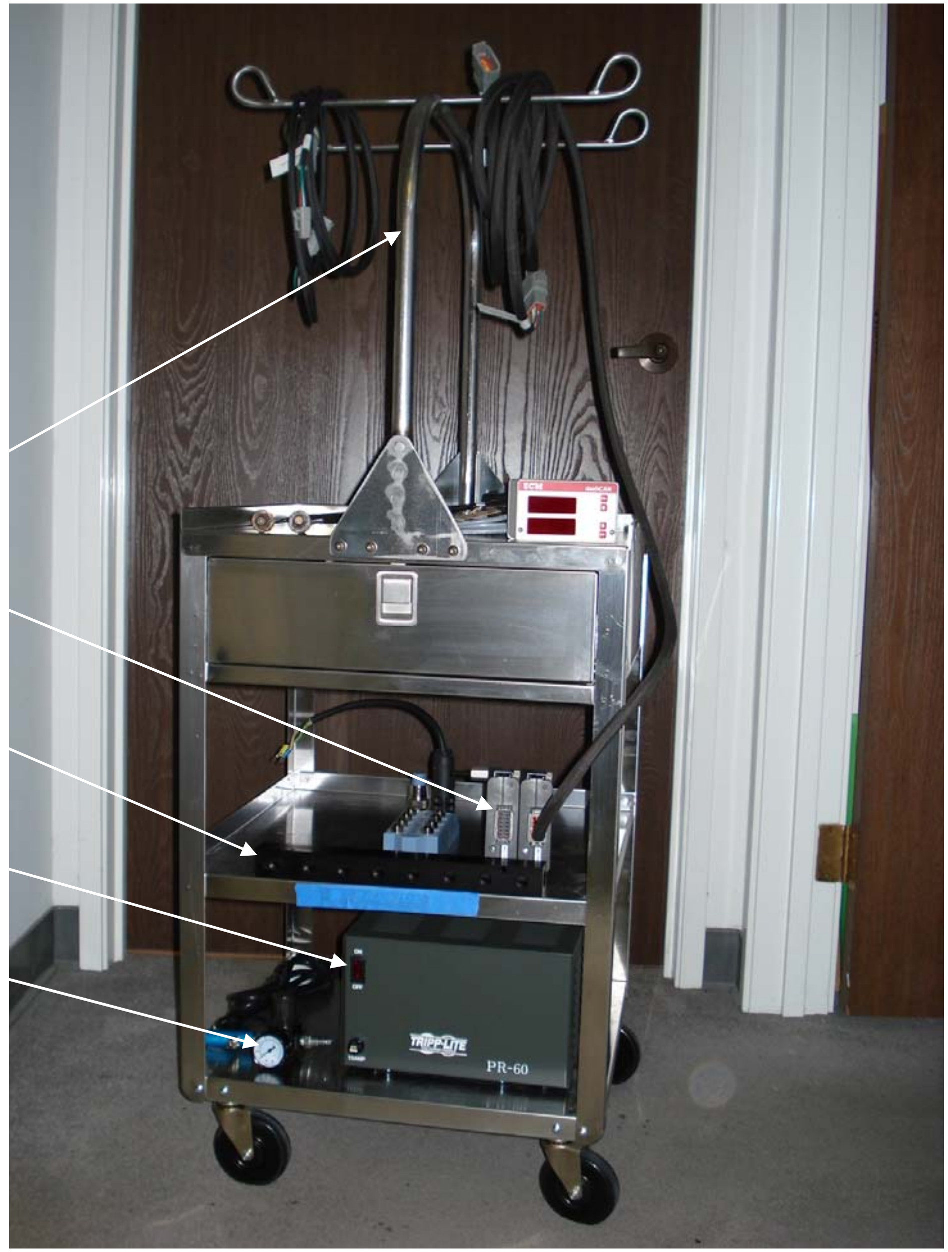
Cable Hangers

LambdaCAN Controllers

Pump Manifold

Power Supply

Pump



ECM Advantage – Versatility

- Suitable for dynamometer and in-vehicle use
- Modular. Easily build multi-channel systems.
- Widest measurement range. Fastest response.
- Can use NTK, Bosch, and Delphi sensors for Lambda, AFR, %O2
- Can use NTK and NGK NOx sensors
- All parameters including raw sensor data (Ip, Rpvs, Age Factor) available
- Programmable fuels (H:C, O:C, N:C, and H_2), sensor control (Rpvs, etc), and delta
- All ceramic sensors factory calibrated and user can easily recalibrate (memory chip)
- Optional automatic pressure-compensation and humidity-compensation
- Supports complete in-house system calibration and verification
- CAN, Analog Outputs (6 ch.), RS232, USB
- Programmable CAN communication. Broadcast and CANopen. .DBC produced.
- Compatible with ETAS INCA (as Add-on) and ATI Vision