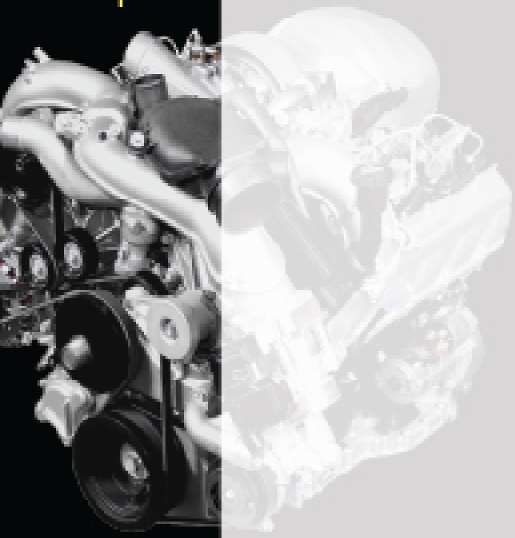
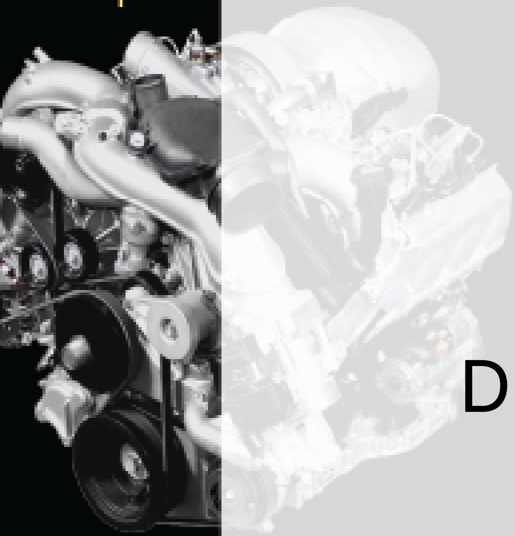


Air-Fuel Ratio Cylinder Imbalance Monitoring

Hal Zatorski
Chrysler Group LLC
SAE OBD Symposium
Indianapolis
September 22 -24, 2009

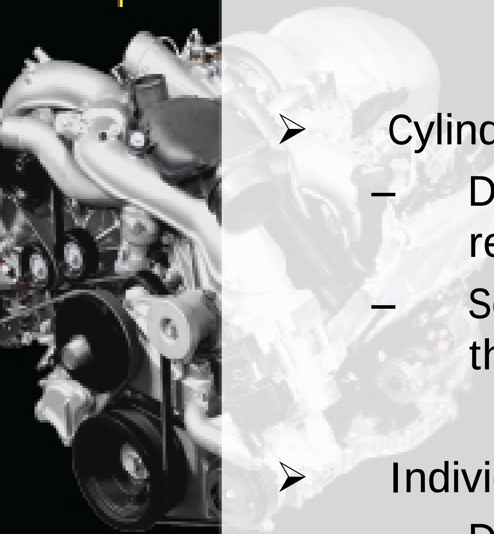
CARB Requirement for Cylinder Imbalance

(C) Except as required in section (e)(6.2.6), for 25 percent of all 2011 model year vehicles, 50 percent of all 2012 model year vehicles, 75 percent of all 2013 model year vehicles, and 100 percent of all 2014 model year vehicles, an air-fuel ratio cylinder imbalance (e.g., the air-fuel ratio in one or more cylinders is different than the other cylinders due to a cylinder specific malfunction such as an intake manifold leak at a particular cylinder, fuel injector problem, an individual cylinder EGR runner flow delivery problem, an individual variable cam lift malfunction such that an individual cylinder is operating on the wrong cam lift profile, or other similar problems) occurs in one or more cylinders such that the fuel delivery system is unable to maintain a vehicle's emissions at or below: 4.0 times the applicable FTP standards for PC/LDT SULEV II vehicles and 3.0 times the applicable FTP standards for 2011 through 2013 model year vehicles; and 1.5 times the applicable FTP standards for 2014 and subsequent model year vehicles. In lieu of using 1.5 times the applicable FTP standards for all 2014 model year applications, for the 2014 model year only, a manufacturer may continue to use 3.0 times the applicable FTP standards for any applications previously certified in the 2011, 2012,or 2013 model year to 3.0 times the applicable FTP standards and carried over to the 2014 model year.



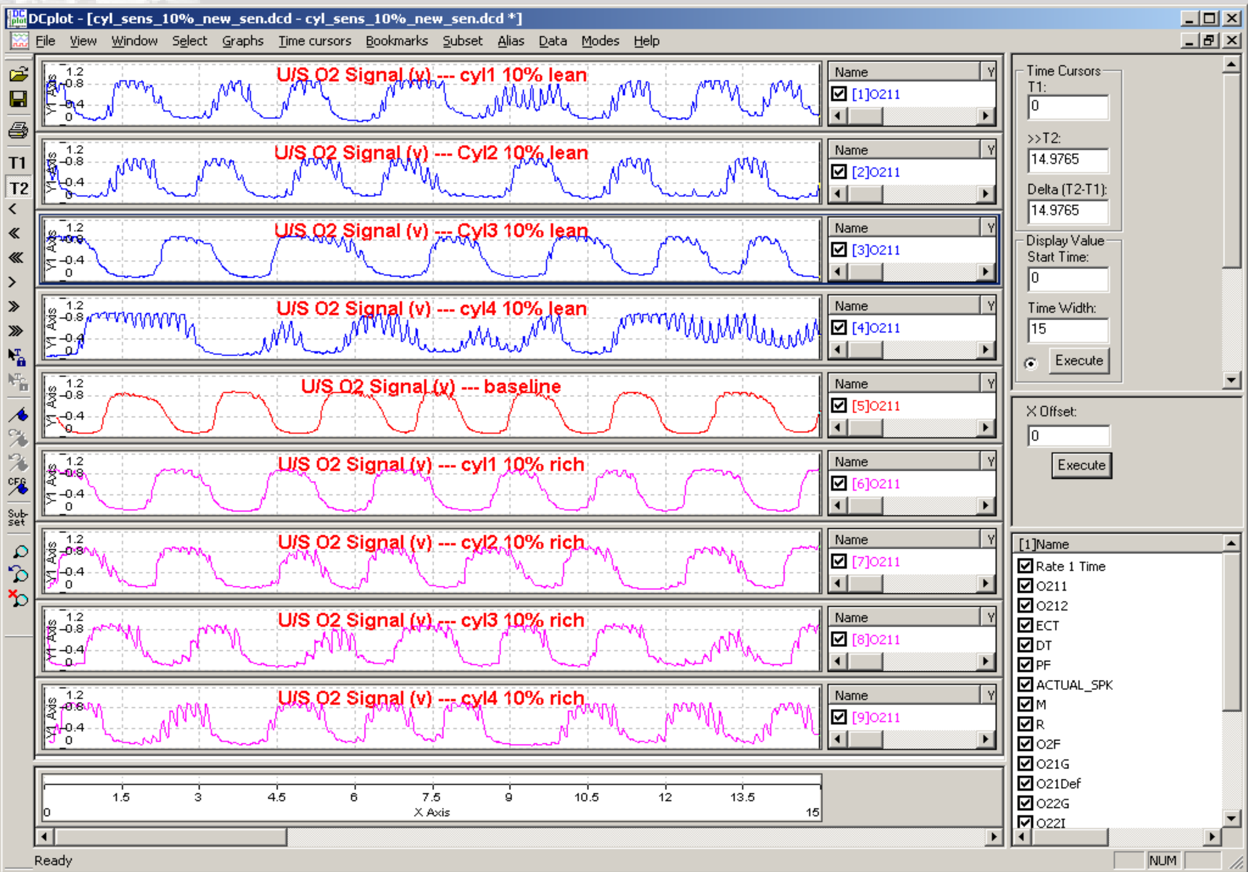
Diagnostic Requirement Justification

Test Procedure Used



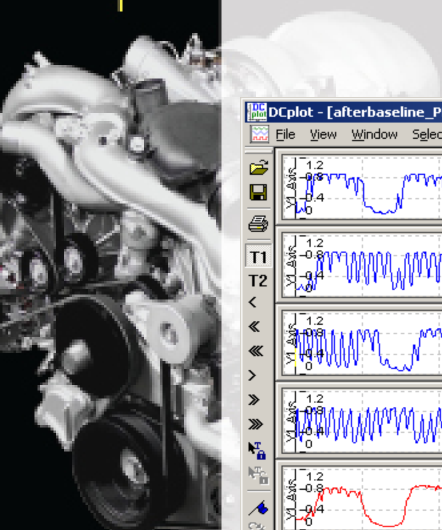
- Cylinder Sensitivity Study
  - Dial each individual cylinder rich then lean, examine U/S O_2 sensor responses
  - Select the cylinder that has the largest impact on the O_2 sensor signal as the test cylinder (single cylinder imbalance test)
- Individual Cylinder Dialing and Emissions Tests
  - Dial total working pulse width multiplier for cylinder x (closed-loop)
  - C80 + Highway FEC Tests
- Data Analysis and Impact Identification
  - Emissions effects
  - Fuel System Monitor response

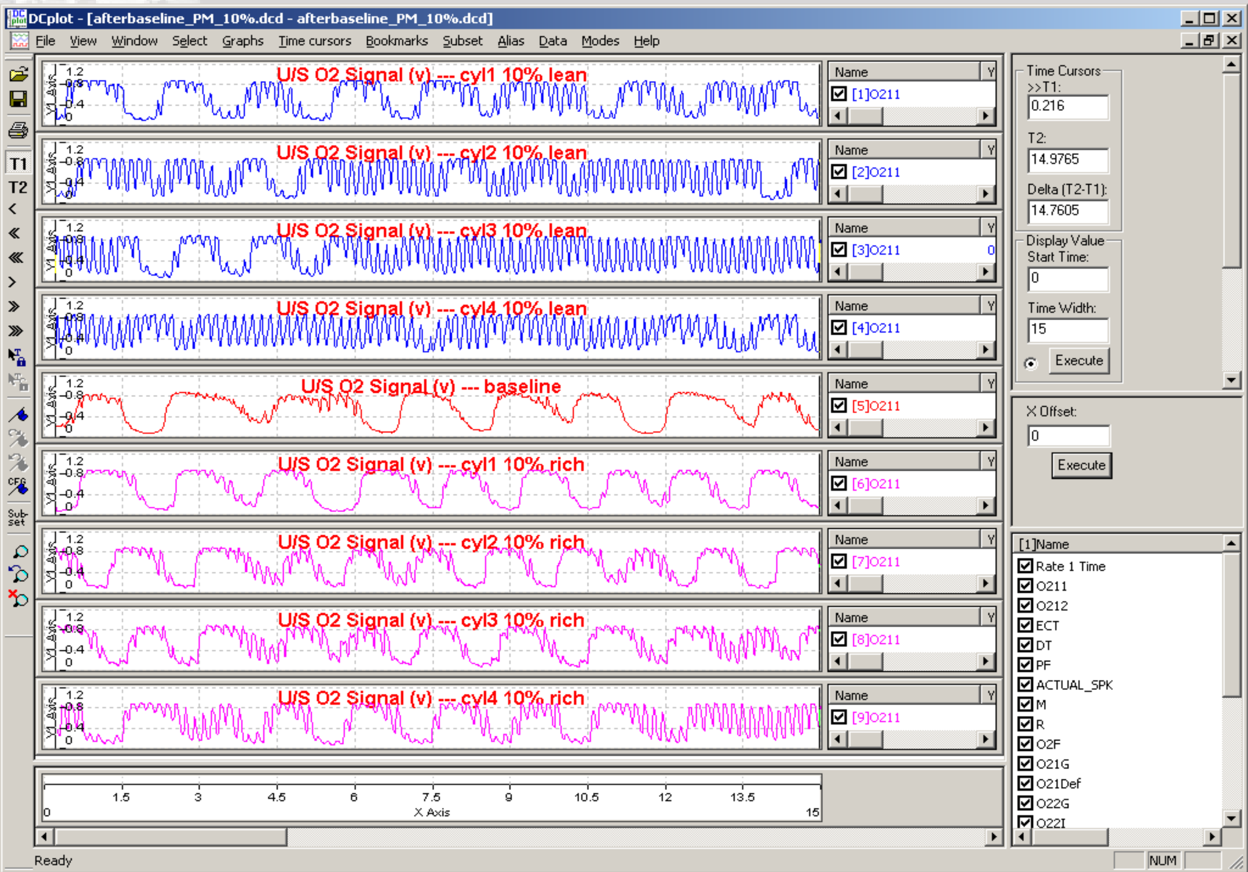
O_2 Responses (New Sensor)



- Dial 10% imbalance at warm idle
- O_2 signal becomes noisier when cylinder imbalance exists

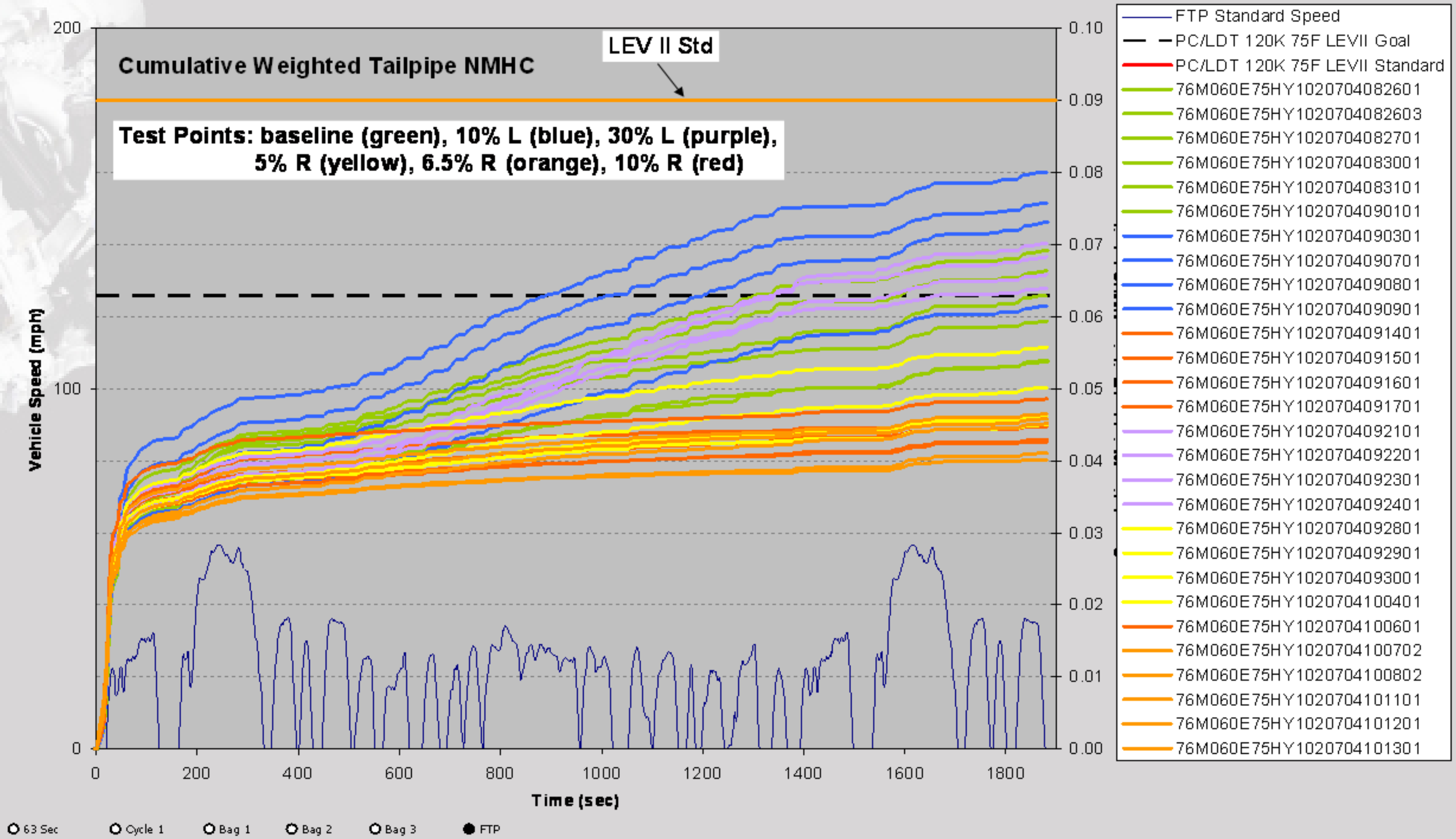
O_2 Responses (500-mile Sensor)



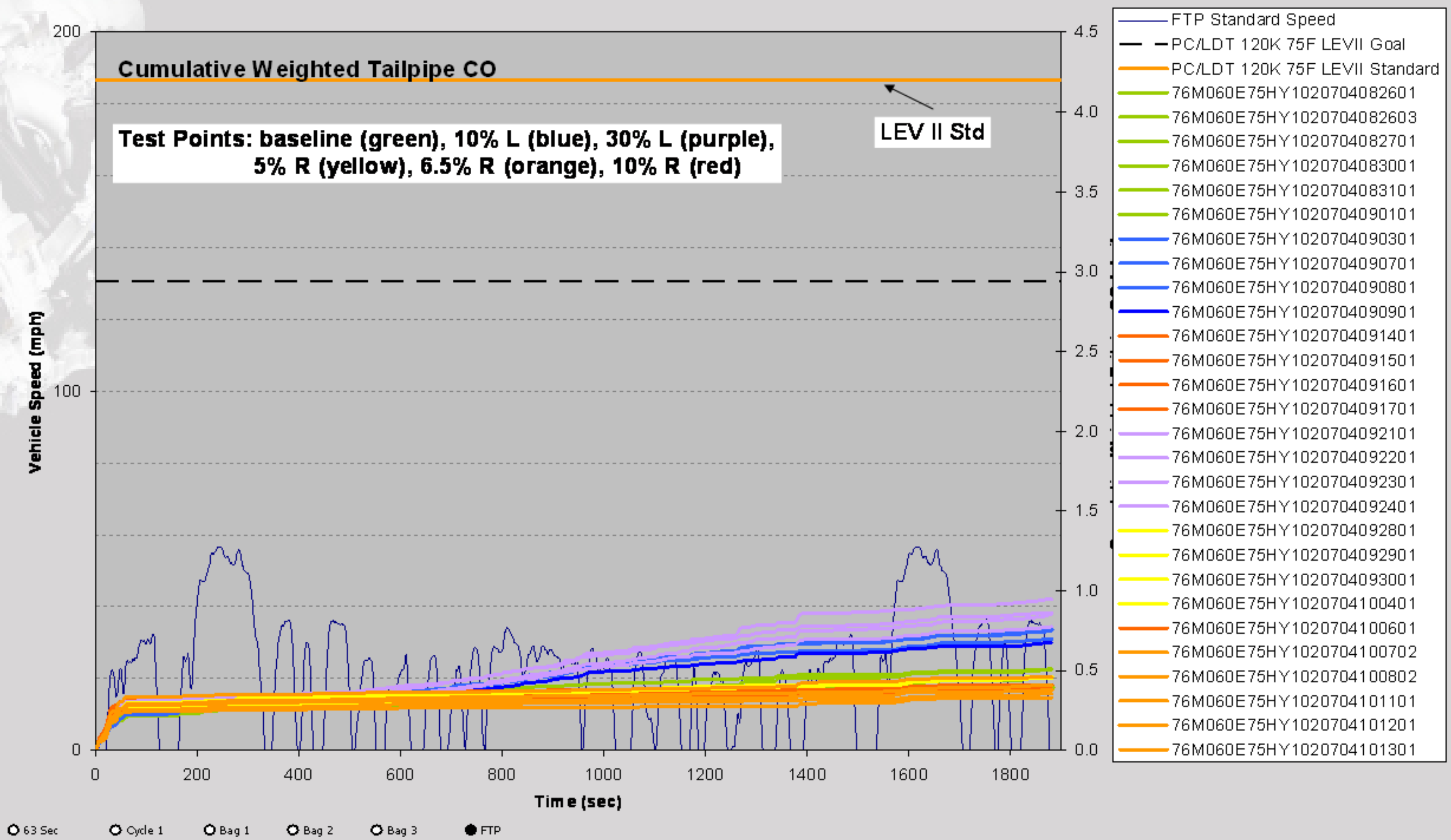


- Trend is more obvious as sensor ages further
- Statistically, cylinder 4 shows biggest impact on O_2 response, and was thus selected as test cylinder

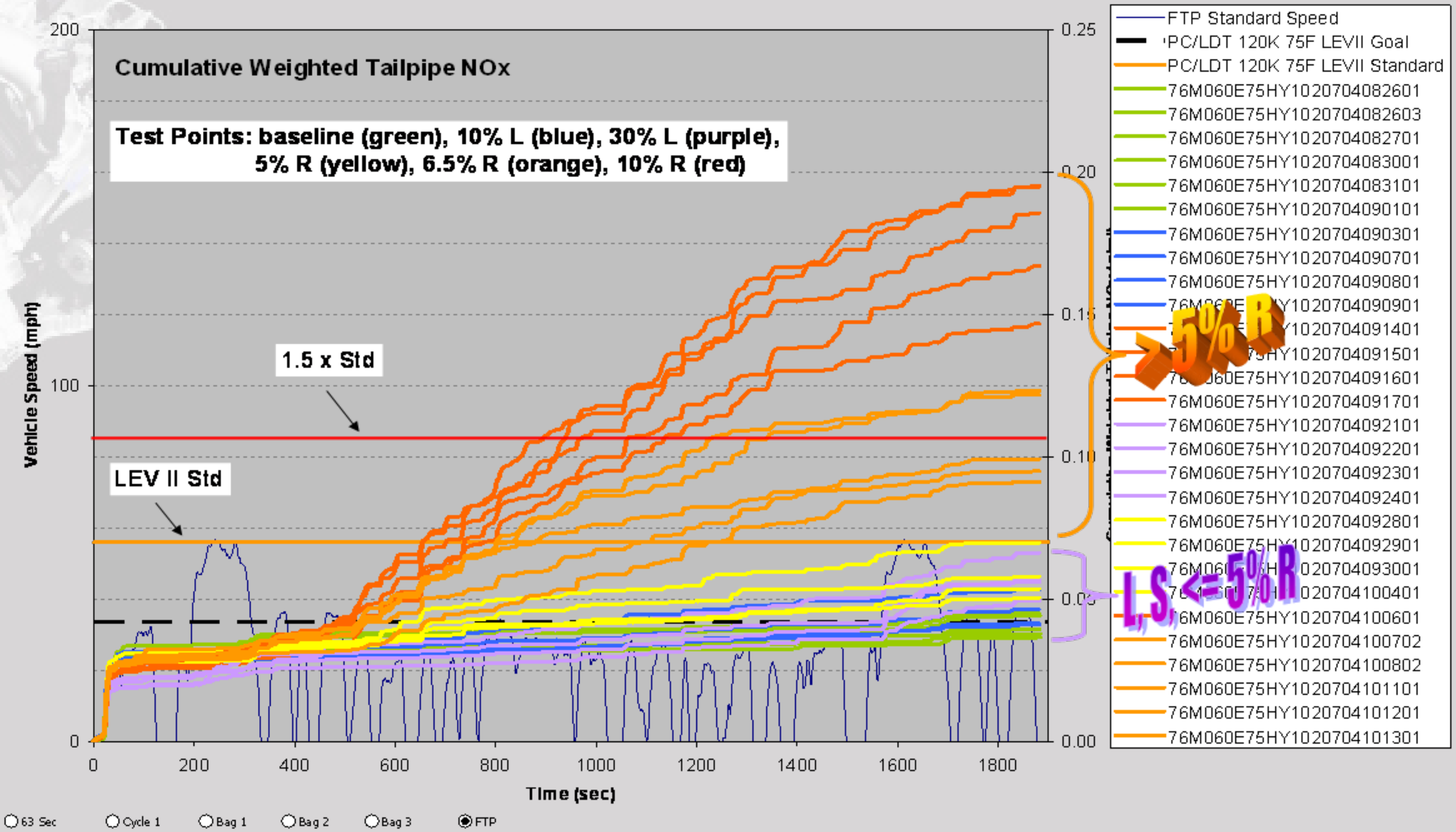
Cumulative Tailpipe NMHC (C80)



Cumulative Tailpipe CO (C80)

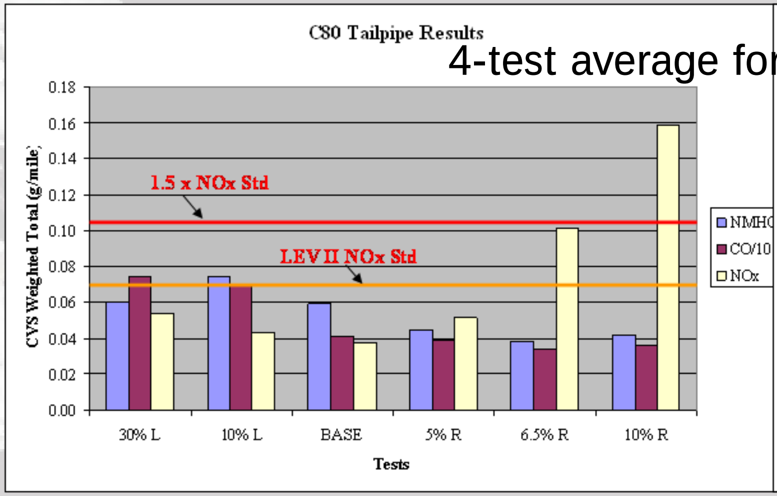


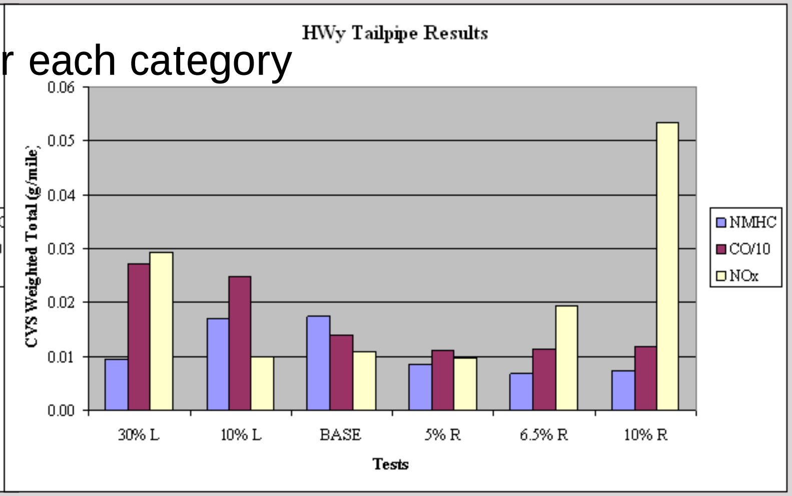
Cumulative Tailpipe NOx (C80)



Test-Averaged CVS Total Tailpipe Emissions

4-test average for each category



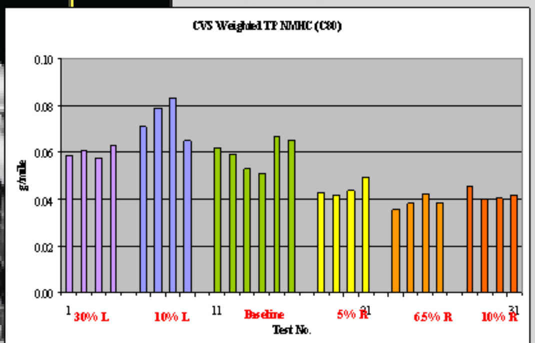


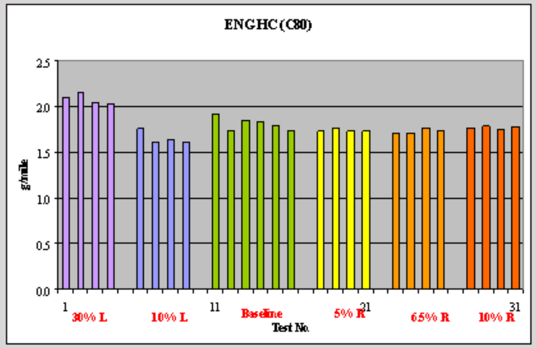
	C80			HWy		
	NMHC	CO	NOx	NMHC	CO	NOx
30% L	0.6%	81.7%	43.5%	-45.4%	96.0%	168.8%
10% L	25.7%	69.8%	15.4%	-2.6%	78.8%	-8.6%
BASE	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
5% R	-25.3%	-5.0%	38.1%	-50.0%	-19.1%	-10.6%
6.5% R	-35.2%	-16.5%	168.6%	-61.0%	-18.7%	77.8%
10% R	-29.7%	-11.7%	321.8%	-56.8%	-13.8%	388.4%

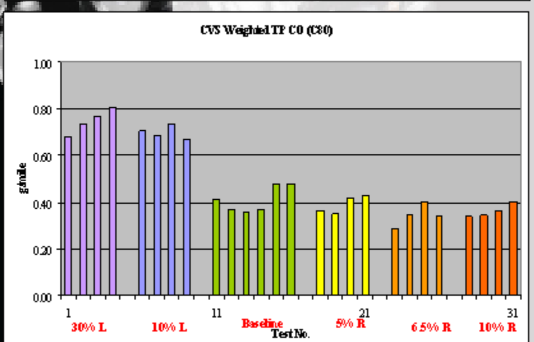
lower NMHC & CO, much higher NOx

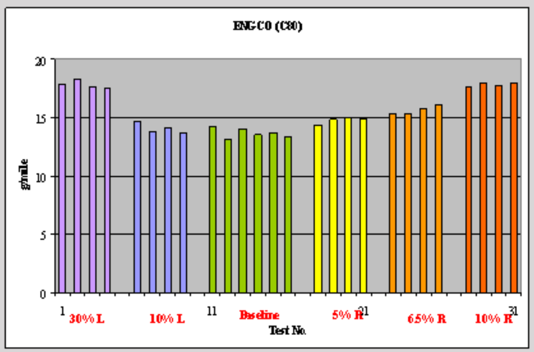
higher CO & NOx; Different NMHC trends: Hwy: drops, C80: goes up then falls down

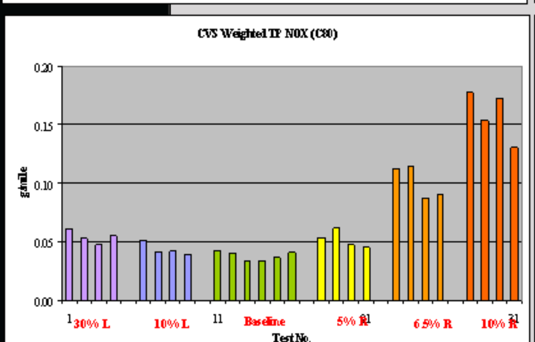
C80 TP vs. ENG Emissions

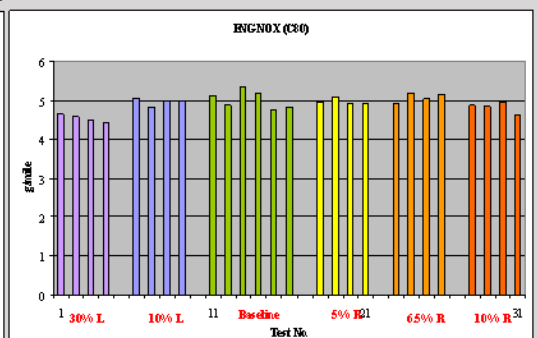






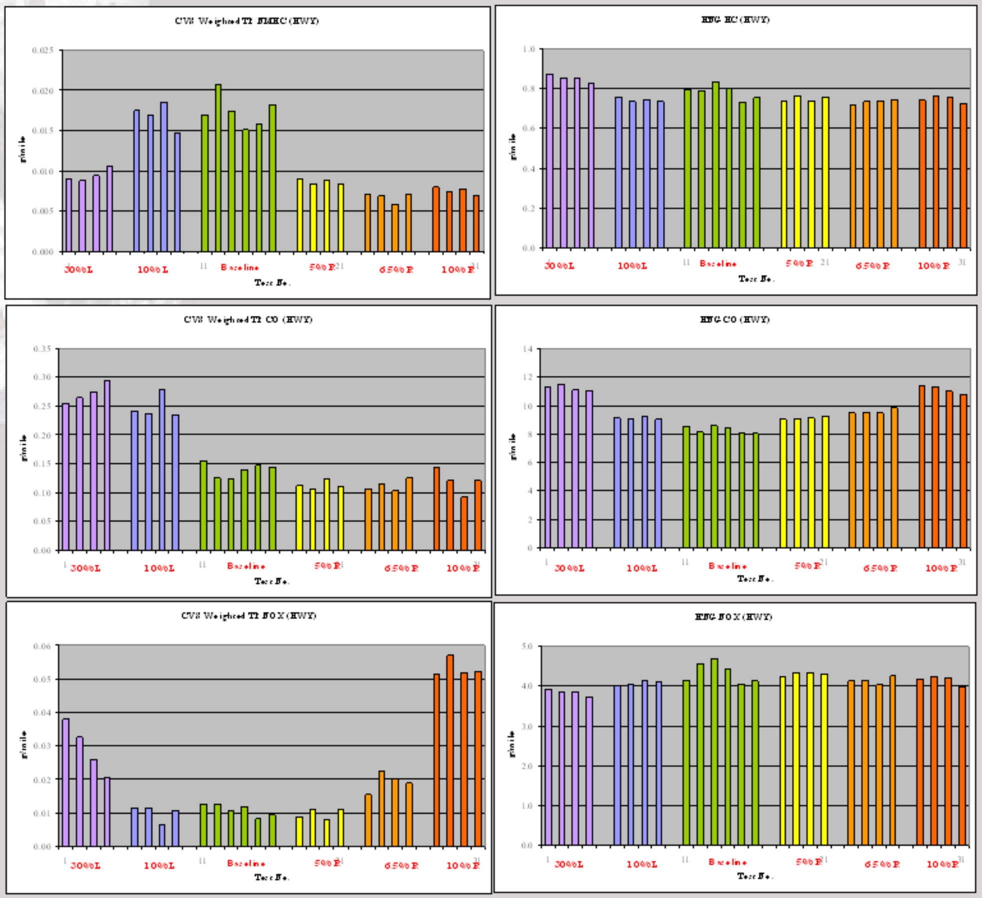






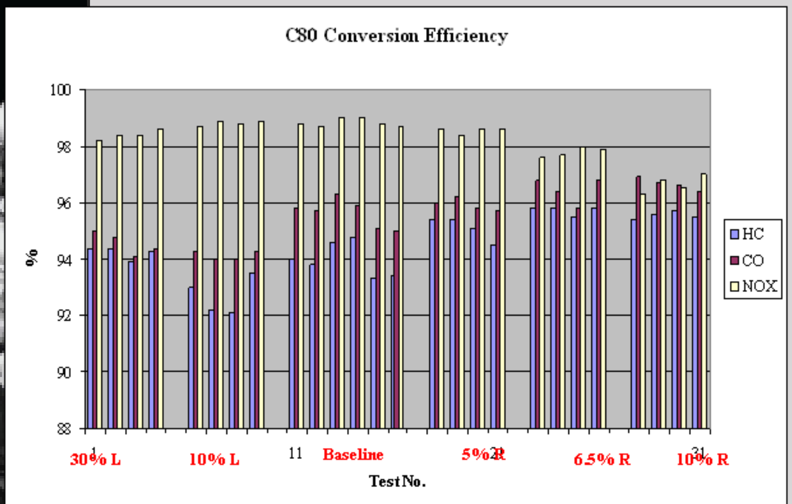
- Dial One Cylinder 10% Lean:
  - lower ENG HC, same ENG CO & NOx
  - higher TP NMHC and CO (deteriorated converter efficiency due to lack of oxidants)
- Dial One Cylinder 30% Lean:
  - higher ENG HC and CO, lower ENG NOx (more significant adaptive effect — to the rich side)
  - same or even less TP NMHC and CO compared with the 10% lean case Dial One Cylinder up to 10% Rich
- Dial One Cylinder up to 10% Rich:
  - same ENG HC and NOx, higher ENG CO (as it is very sensitive to rich f/a)
  - same or lower TP NMHC and CO (Lean exhaust gas coming from the other three cylinders promotes HC and CO oxidation)
  - very high TP NOx (due to reductant-competition and “messed-up” oxygen storage control)

Hwy TP vs. ENG Emissions



- Similar but more obvious trends compared with C80
- More steady state driving gives more opportunity for adaptive cells to update

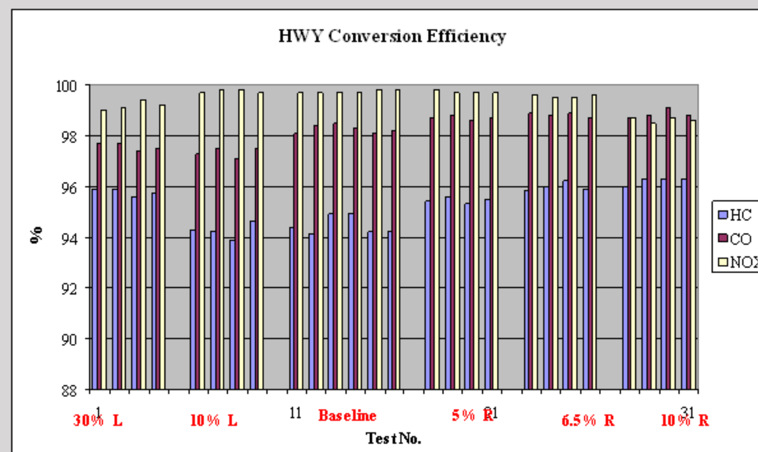
Conversion Efficiencies



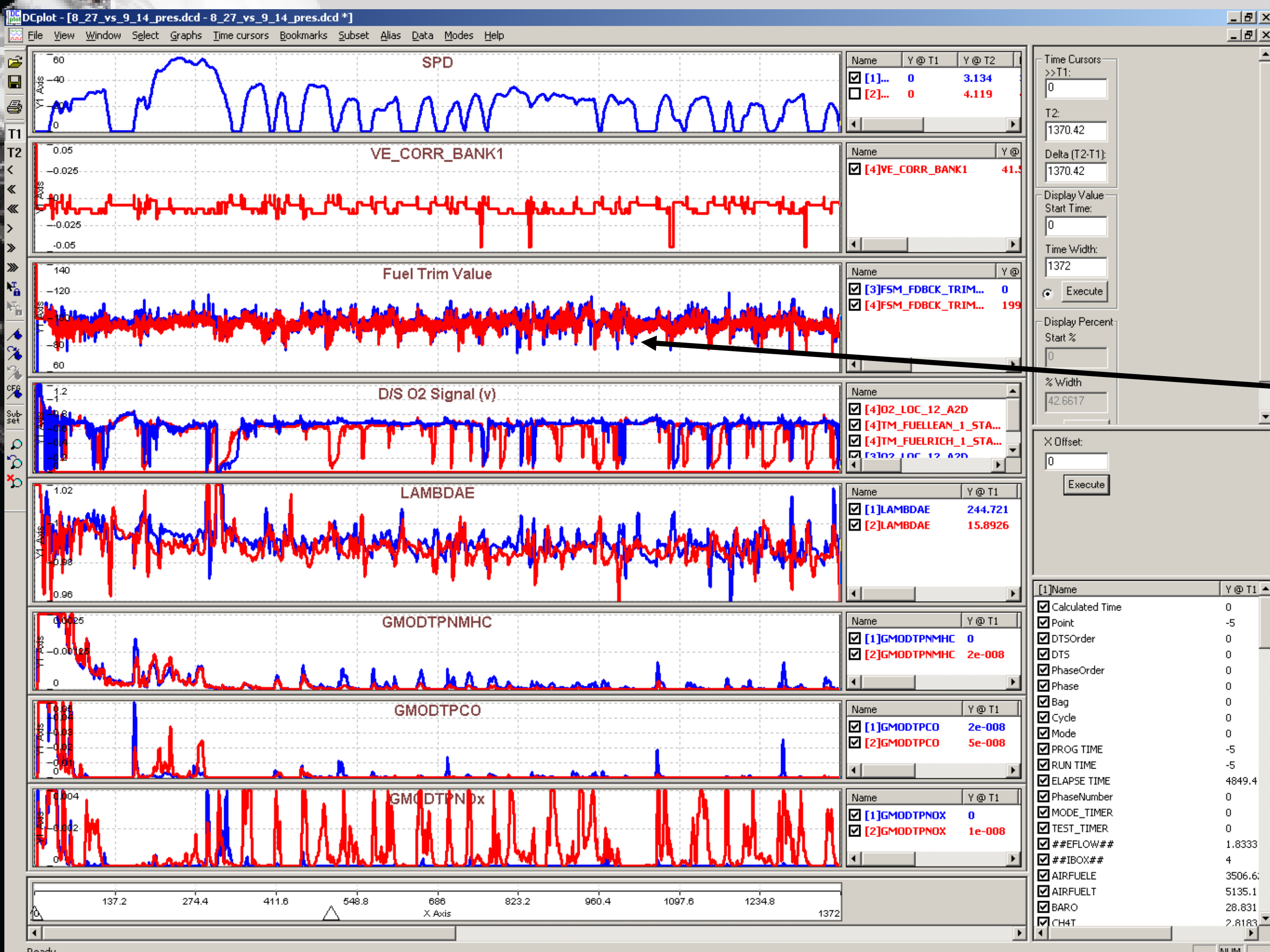
Sufficient oxidants makes HC and CO efficiencies increase; reductant-competition and “messed-up” oxygen storage control causes NOx efficiency to drop dramatically.

Oxidants deficiency makes HC, CO efficiency drop; non-optimal oxygen storage management causes NOx efficiency to drop as well.

Aged catalysts need small and high-frequency perturbations to maintain good conversion efficiencies.



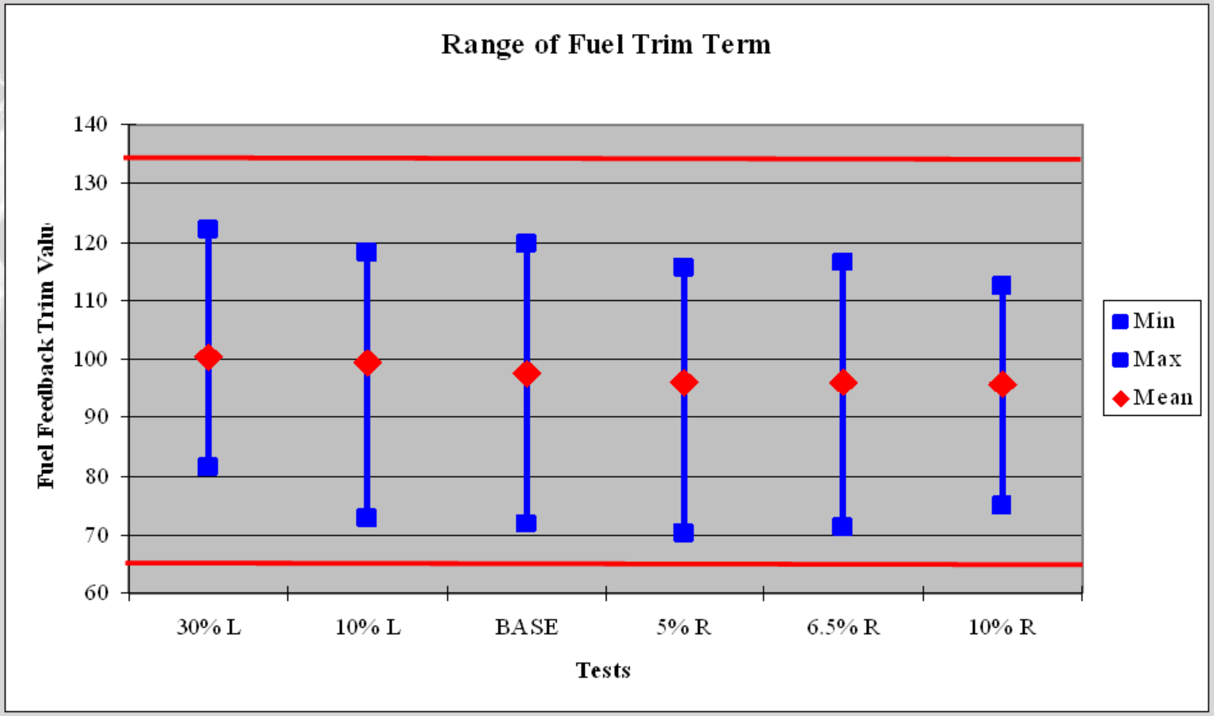
Fuel System Monitor & MIL



Cyl 4 10% R (red) vs. baseline (blue)

Fuel Trim Term stays in range despite high NOx; MIL was not set

Fuel Feedback Trim Term

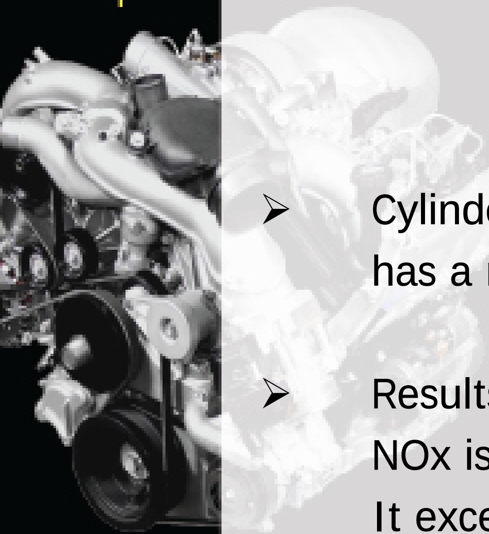


- Imbalance does not significantly change the range of Fuel Trim Term.
- Fuel Trim Thresholds are ± 35 % (red lines). Fuel System Monitor MIL was never set in any of the tests.
- No other MIL (e.g. Misfire) was set.

Potential Injector Issues Causing Imbalance

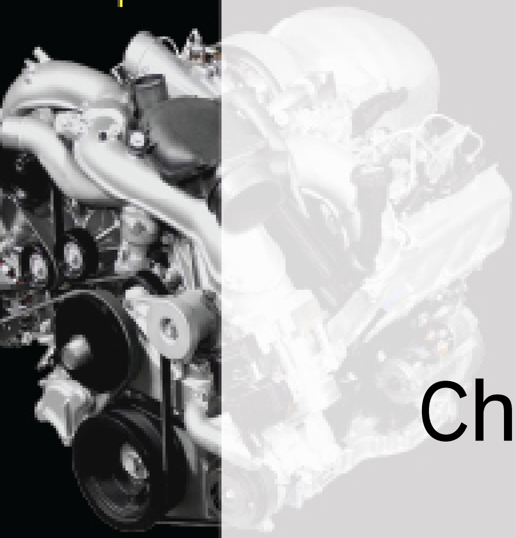
- Injector Flow Tolerances
  - Static
    - new ± 3%
    - aged + 6% ~ -4%
  - Dynamic
    - ± 8%
- Common Injector Failure Modes Leading to Rich Imbalance
  - Stuck Open
  - Prolonged Closing Time
  - Leakage due to Contamination
  - ...

Each of these could cause over 5% rich imbalance (NOx tolerance)



Justification Summary

- Cylinder imbalance significantly affects after-treatment reactions, and thus has a major impact on tailpipe emissions and OBD.
- Results from a LEV II package equipped with 120 K aged catalyst show that NOx is at the borderline of std when 5% single cylinder rich imbalance exists. It exceeds 1.5x std when there is as little as 6.5% rich imbalance.
- Although Chrysler does not have EGR distribution tube, injector tolerance range is significant enough to induce such imbalances.
- Technically, individual cylinder fuel control, working along with O_2 Control, should be able to remove the imbalance to some extent.



Chrysler Monitoring Requirements

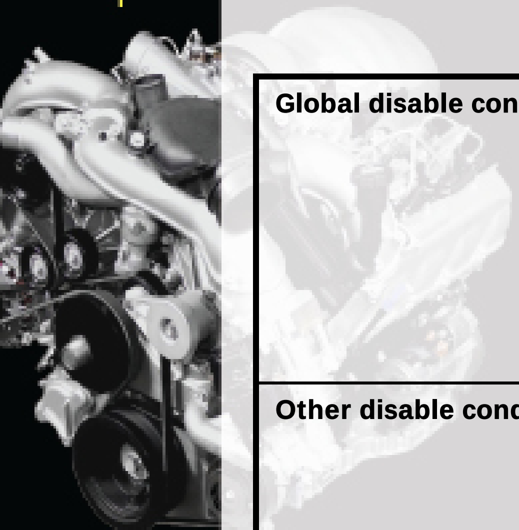
Monitoring Requirements

Air-Fuel Ratio Cylinder Imbalance	The OBD II system shall monitor an air-fuel ratio cylinder imbalance (e.g., the air-fuel ratio in one or more cylinders is different than the other cylinders due to a cylinder specific malfunction such as an intake manifold leak at a particular cylinder, fuel injector problem, an individual cylinder EGR runner flow delivery problem, an individual variable cam lift malfunction such that an individual cylinder is operating on the wrong cam lift profile, or other similar problems) occurs in one or more cylinders such that the fuel delivery system is unable to maintain a vehicle's emissions (section 6.2c)
MIL (Malfunction Indicator Lamp) requirement when either condition is met	Tailpipe emissions (or a part of it) exceeds the standard below at full useful life mileage or 3.0 X standard in 2011MY – 2013MY 1.5 X standard in 2014MY+ Two (2) Trip Failure to Illuminate the MIL
Demonstration Reporting	Production Vehicle Evaluation (PVE) testing & reporting
Legislative Diagnostics	mode 6 will likely be required later
Rate Based Monitoring	See next page

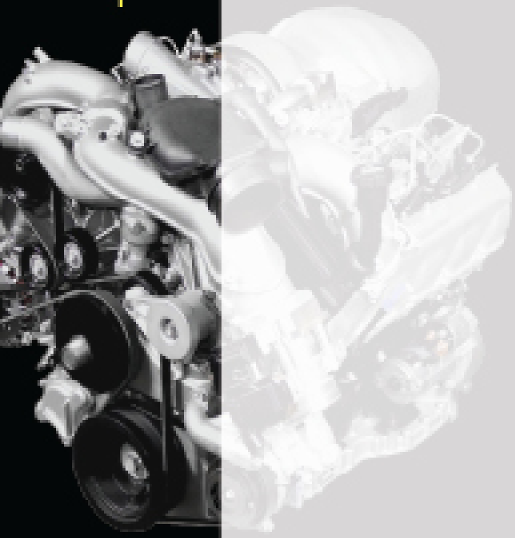
Rate Based Monitoring

In-use performance ratio	**(Numerator / Denominator) >= 0.1**
	Chrysler solution = ensure monitor enable conditions within a known imbalance measure window, usually from dyno data, minimize conflict conditions
Numerator	**The number of times a vehicle has been operated such that all monitoring conditions necessary to detect a failure have been encountered**
	The numerator can only be incremented once per driving cycle
Denominator	**The number of times a vehicle has been operated beyond the minimum requirements for a standard driving cycle**
Standard drive cycle	**Cumulative time with vehicle speed above 25mph > 300 seconds** – **Less than 8000 feet elevation** – **Ambient temperature above 20 degrees F** **Cumulative time at idle > 30 seconds** – **Less than 8000 feet elevation** – **Ambient temperature above 20 degrees F** **Cumulative time engine is running > 600 seconds** **Following a cold start**
Reporting requirements	**Results collected on California vehicles and reported annually to CARB**

Enable Criteria, In- Plant



Global disable conditions	**Common disable conditions CARB accepts for many diagnostics with approval** – **Below 20 degrees F** – **Above 8,000 feet in elevation** – **Battery Voltage below 11.0 volts** – **Fuel level less than 15 %** – **With PTO engaged**
Other disable conditions	**Cylinder Imbalance Monitor is not required to run when:** – **Any signal used as an input has a failure** – **During a driving condition that may cause a false pass or false fail situation** **Chrysler uses Stop, Suspend and Conflict tables for some of these conditions**
In-plant diagnostics	**In-plant testing not feasible due to enable criteria and plant process limitations**



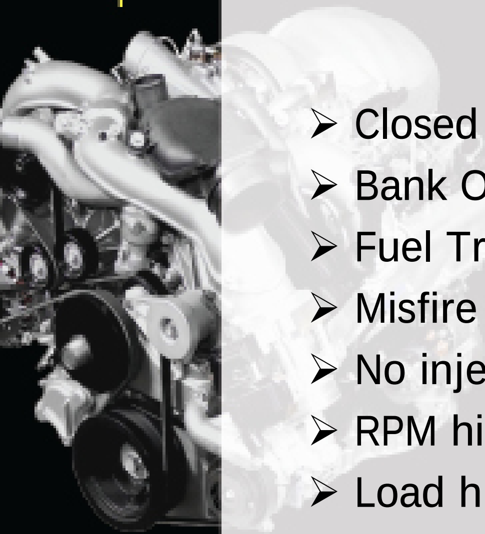
High Level Intent Based On CARB Reviews

High Level Implementation Intent

- Non-Continuous Monitor - runs once per trip when the enable conditions are met (i.e. closed loop fuel control, RPM/MAP window are satisfied)
- 2 trips to set MIL
- In-Use Ratio Monitoring required (one element of Fuel System Monitor)
- 2 Pcodes - 1 per bank planned
- Additional fault detection resolution may be possible in the future (individual cylinders)
- No J1979 Mode 6 test results required at present; will likely be a future requirement.

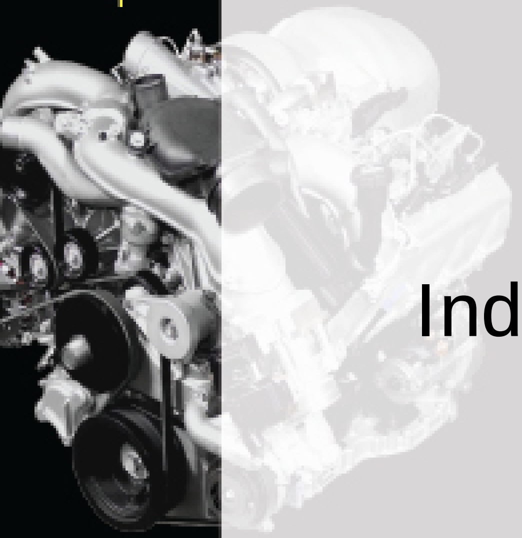
High Level Implementation Intent (continued)

- Mock Demonstration will be performed on an FTP while monitoring the worst case cylinder for that cylinder bank
- In order to identify the worst case cylinder for that cylinder bank, Chrysler will run a Hot 505 for each perturbed cylinder
  - For example, for an 8 cylinder engine, 8 Hot 505 cycles performed in which the fuel-air ratio is perturbed for each cylinder
  - The cylinder with the worst emissions would then be the cylinder monitored for the FTP mock demonstration test



High Level Implementation Intent (continued)

- Closed loop fueling achieved
- Bank O_2 sensor has not failed
- Fuel Trim and Fuel System monitors have not failed
- Misfire monitor has not failed
- No injector faults , knock faults , O_2 heater faults, cam/crank faults.
- RPM high/low window defined
- Load high/low (MAP or charge) window defined
- EGR and Purge limits for adaption/detection not reached
- MDS is not active on appropriate cylinders
- ECT minimum exceeded
- Engine run time minimum exceeded
- TBD level of Ethanol learn completed

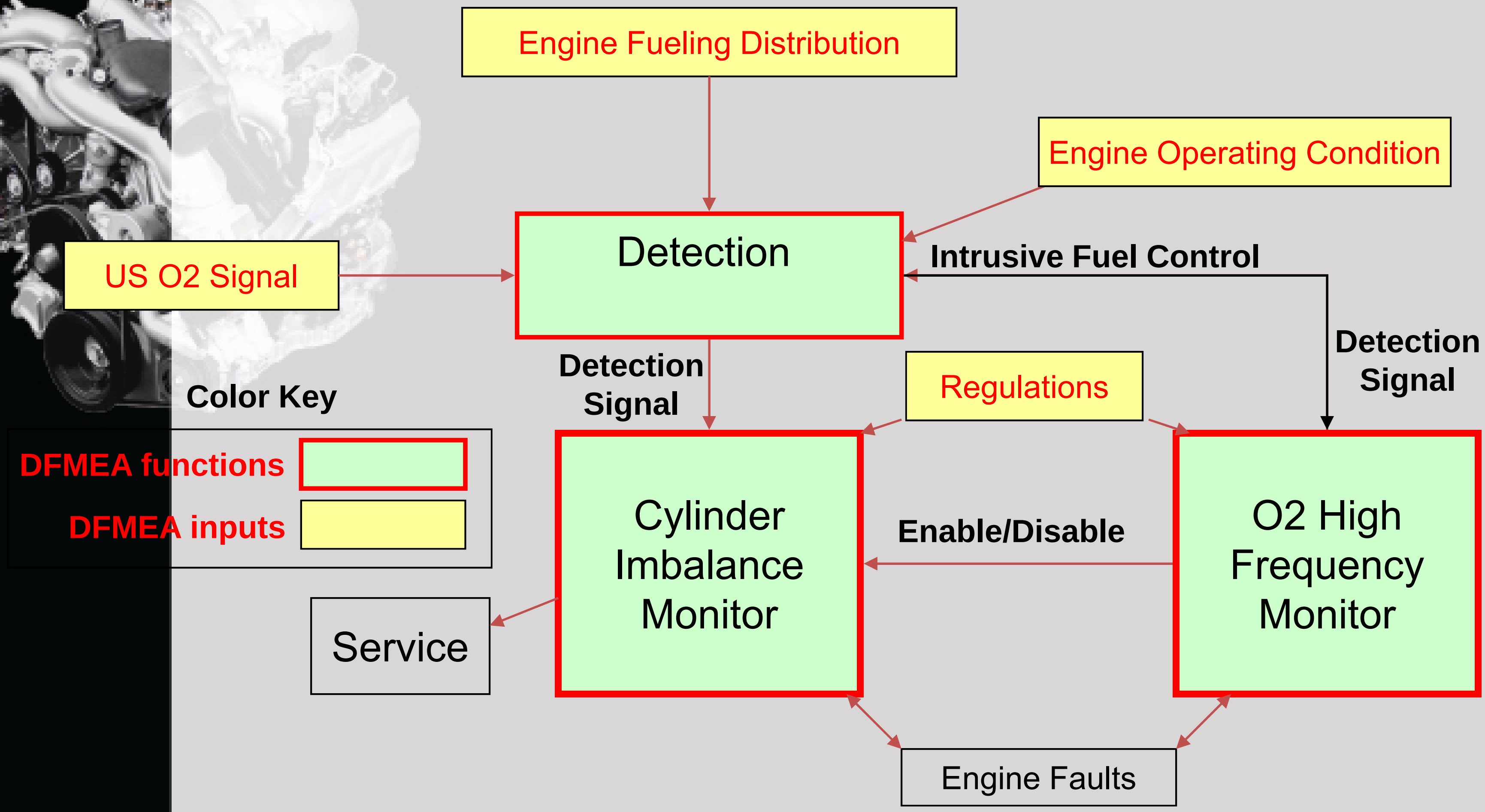


Individual Cylinder Imbalance Detection & O2 Sensor High Frequency Slow Response

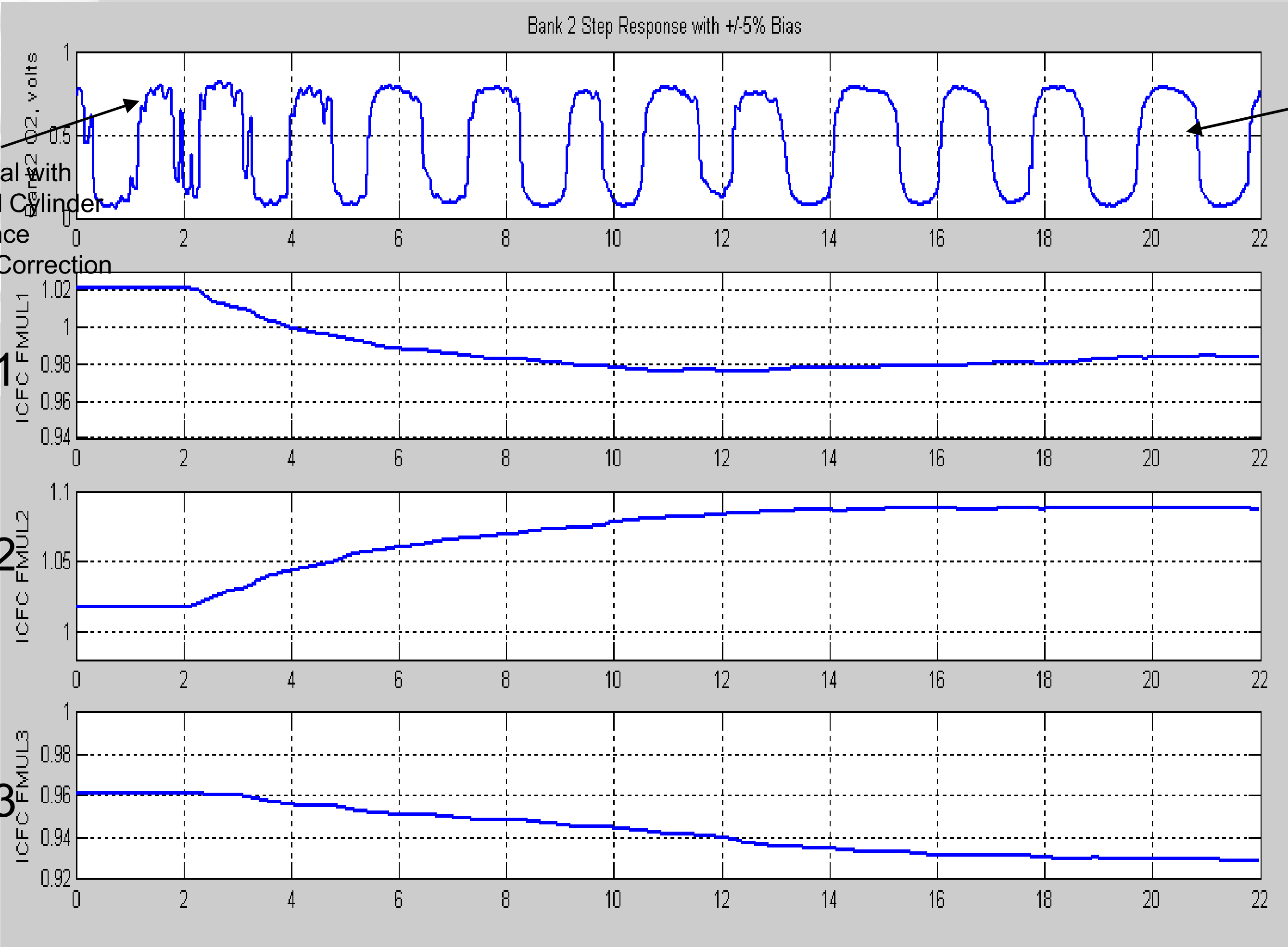
Cylinder Imbalance Detection Method #1: Cylinder Imbalance Detection with Fuel Correction

- Method attempts to eliminate cylinder imbalance with a closed-loop adaptive fuel control strategy
- Uses relative cylinder imbalance information to correct the bank that is out of balance
- Using upstream switching O_2 sensor
- Monitor would look at each cylinder’s adaptive and compare to a calibratable threshold
- Each cylinder has its own imbalance threshold
- System more robust to emissions caused by cylinder imbalance
- The adaptives are applied but not updated when in open loop fuel control

System Boundary Diagram



Cylinder Imbalance Detection Method #1: Cylinder Imbalance Detection with Fuel Correction



Cylinder Imbalance Detection Method #1: Cylinder Imbalance Detection with Fuel Correction

Previous slide shows an example of a bank O_2 sensor in a V6 application

- The method #1 closed loop imbalance detection and fuel correction strategy starts
- Correction begins on the left with the induced rich imbalance
- Cylinders 1 and 3 adapt in the lean direction
- Cylinder 2 adapts in the rich direction
- Detection method looks at the relative imbalance of all cylinders in a bank against a mean
- Fuel correction reduces the high frequency imbalance of bank O_2 sensor signal

Air-fuel Ratio Cylinder Imbalance Key Points

- Air-fuel ratio cylinder imbalance and individual cylinder fuel control cannot function properly with O_2 sensors slower than 850ms
- O_2 monitor must detect an 850ms or slower sensor because air-fuel ratio cylinder imbalance will not function beyond that point
- Drives new O_2 high frequency response monitor to detect when cylinder imbalance signal is too low for imbalance diagnostics

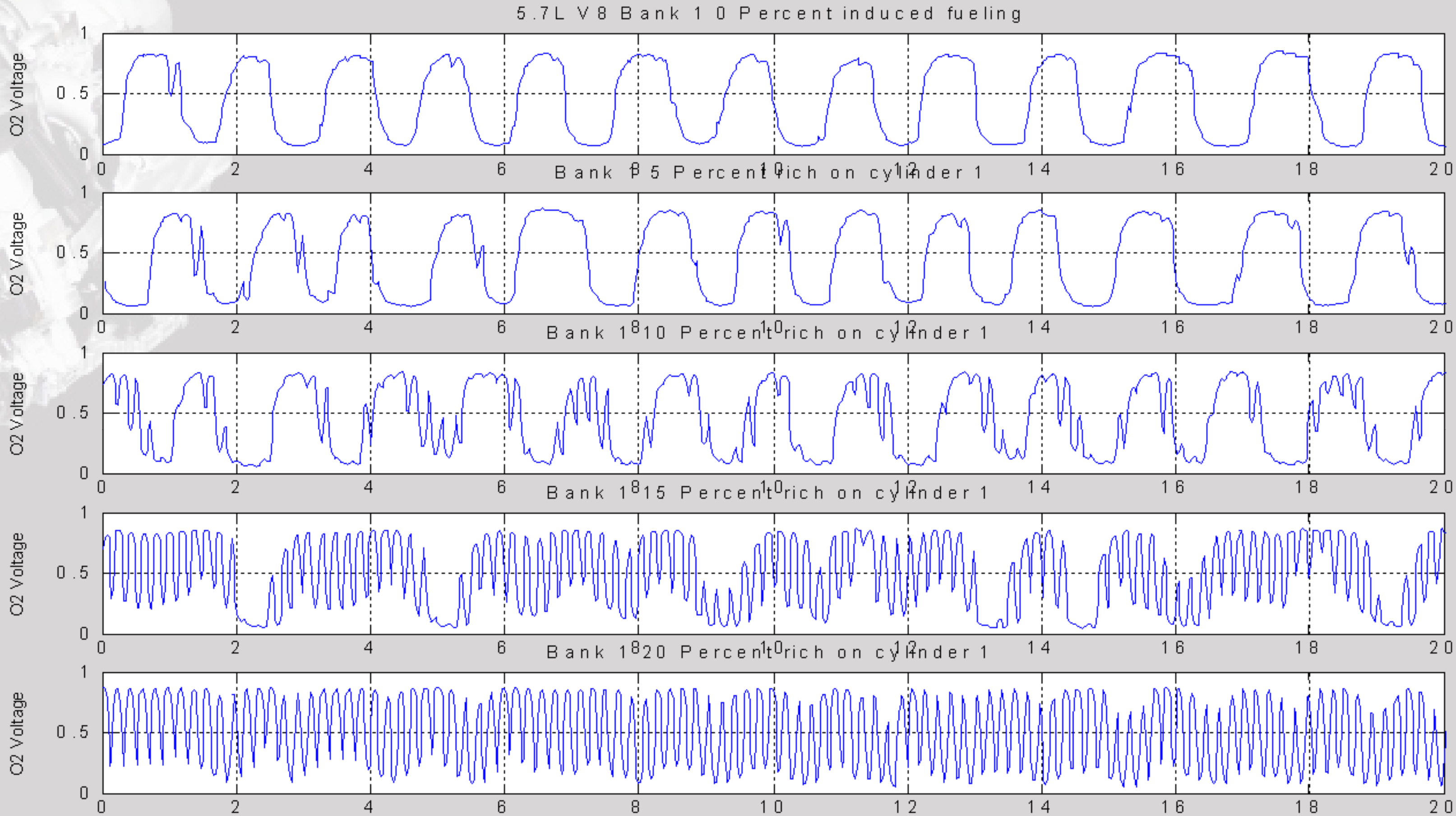
O2 High Frequency Monitor Enable Requirements

- Diagnostic Test Timer < Maximum Test Time
- Engine Coolant Temperature >= Minimum ECT – Hysteresis
- Engine Running Timer >= Minimum Engine Run Time
- Cylinder De-activation is Active and a Calibration Bit is Enabled, then Disable Diagnostic
- Engine Speed (RPM) and Engine Load (Air Charge or MAP) define the enable window

O2 High Frequency Monitor P-codes

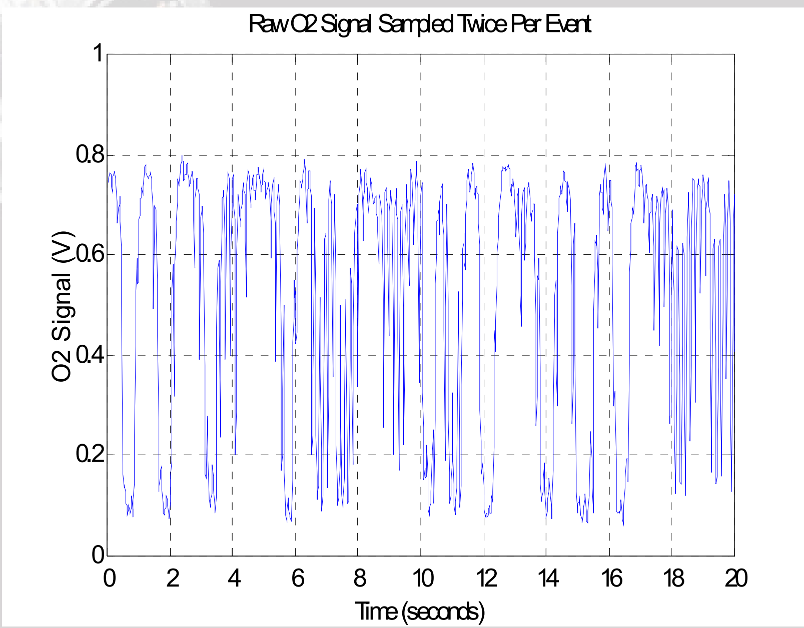
- P113D O2 Sensor 1/1 Slow Response (High Frequency)
- P113E O2 Sensor 2/1 Slow Response (High Frequency)
- Two (2) Trip Fault
- Non-Continuous
- After first "soft" failure (no notification to Diagnostic manager here), intrusive fuel control is required before actual failure is recorded
- Failure is defined as a failure timer >= Minimum fail time
  - Diagnostic Manager is informed of the actual failure after intrusive fuel control
- If Method 1(individual cylinder) is Selected to determine failure,
  - Maximum value of Individual Cylinder Fuel Control Adaptive for all Cylinders of Bank X >= Monitor Minimum Threshold
- If Method 2(Cylinder Imbalance Bank Detector) is Selected,
  - Cylinder Imbalance Bank Detector Signal exceeds O2 High Frequency Monitor threshold

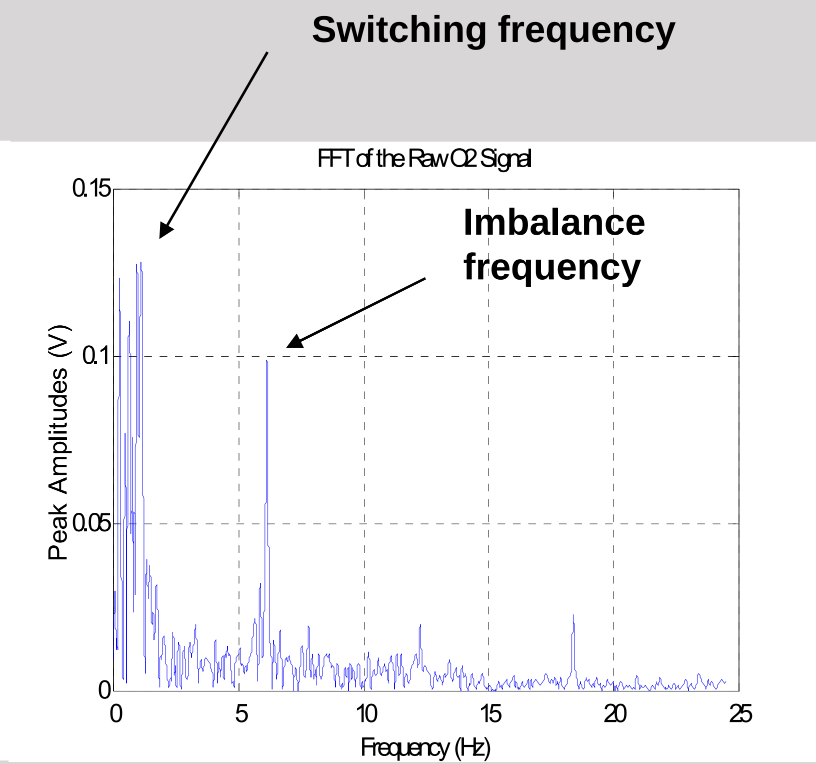
O2 Sensor Data as the amount of imbalance is increased

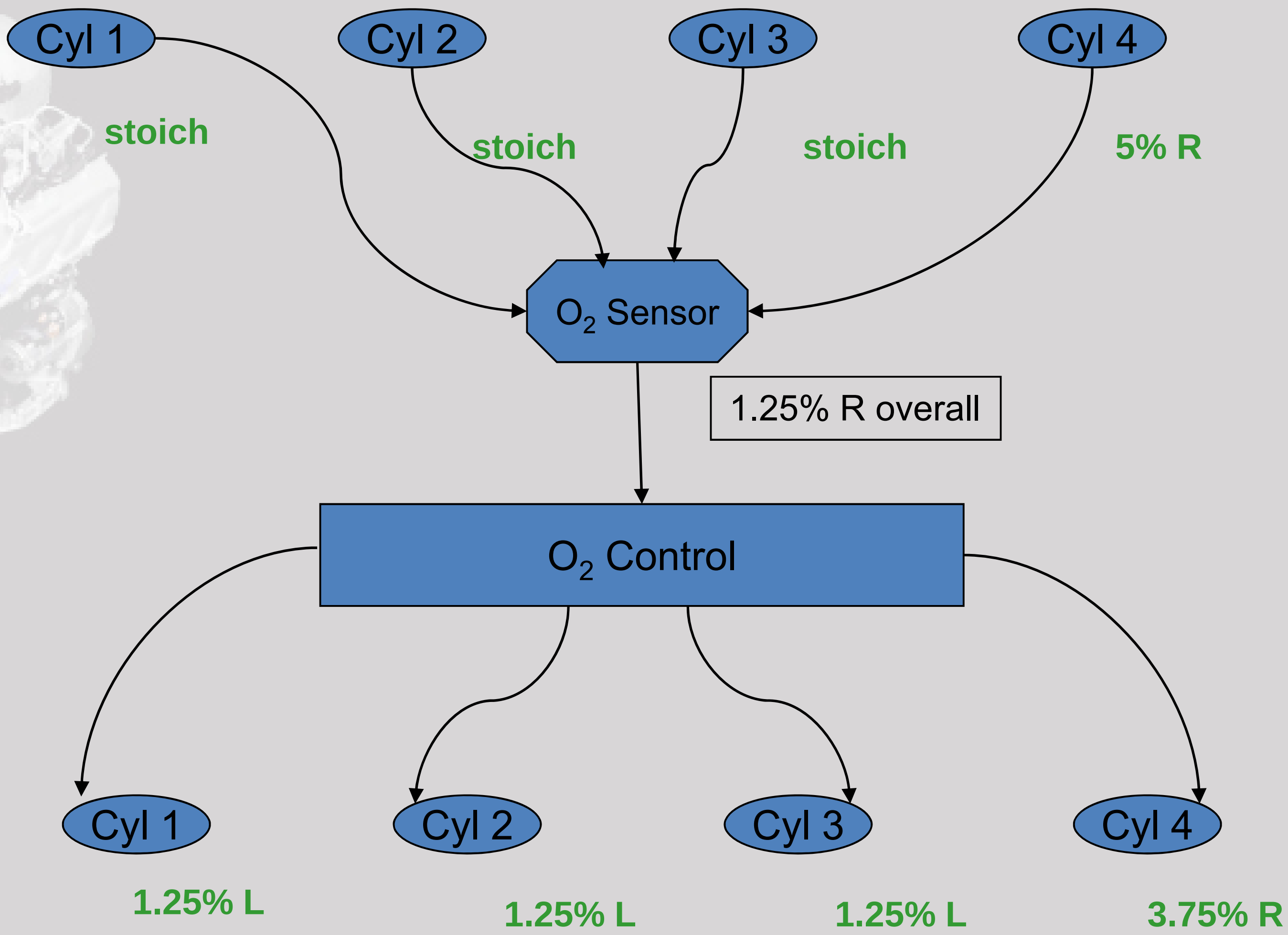


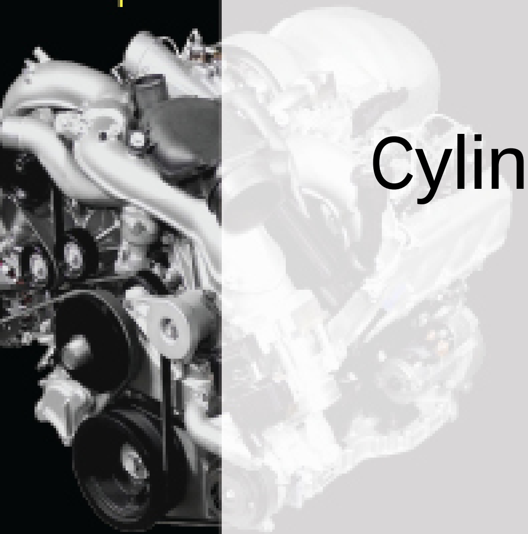
Filtering the O2 Sensor Signal

- Filtering of the O2 sensor signal shows the low frequency switching and the higher frequency imbalance.






Cyl 1
Cyl 2
Cyl 3
Cyl 4
stoich
stoich
stoich
5% R
O2 Sensor
1.25% R overall
O2 Control
Cyl 1
Cyl 2
Cyl 3
Cyl 4
1.25% L
1.25% L
1.25% L
3.75% R

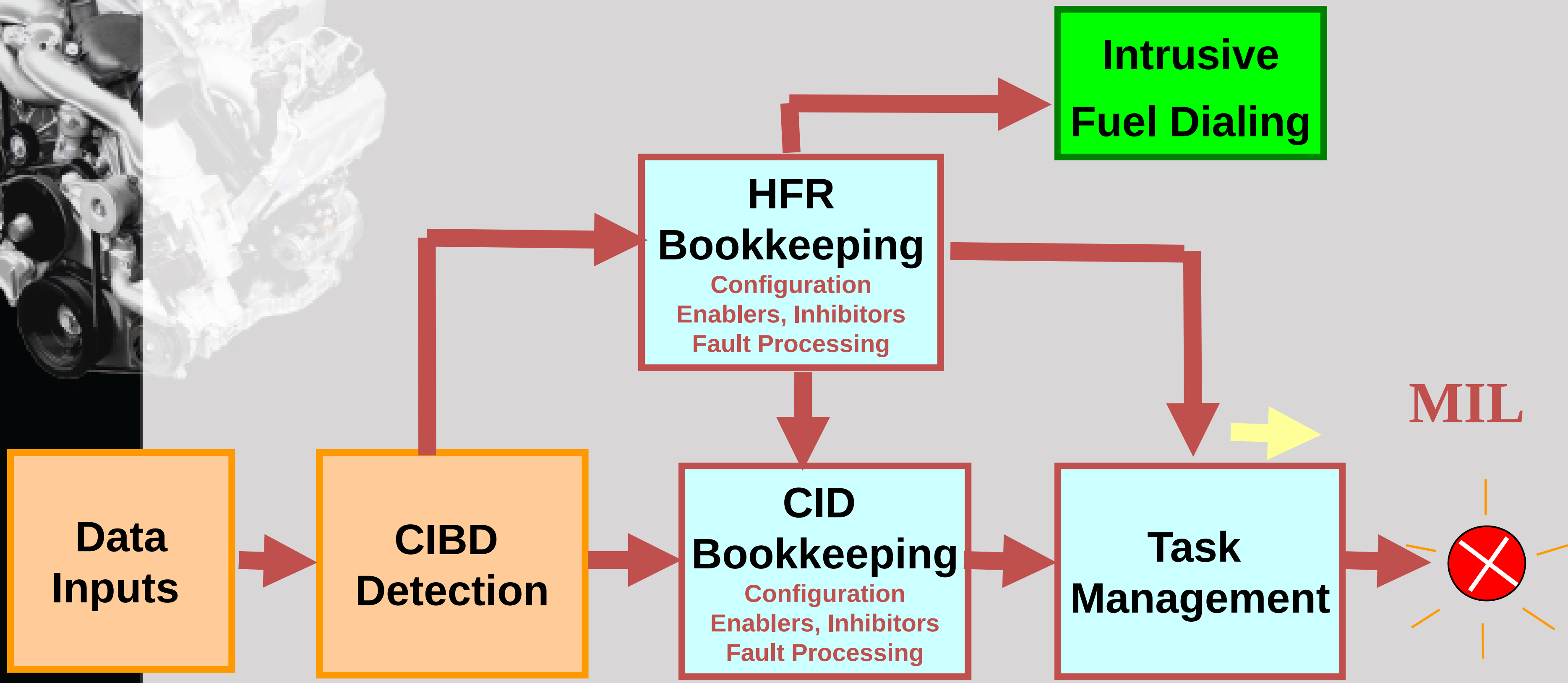


Cylinder Imbalance Bank Detection Method

Cylinder Imbalance Detection Monitor Requirements

- Diagnostic is non-continuous (once per trip, then done for the remainder of the drive cycle)
- 2 P codes – 1 P code Per Bank
- 2 trips to set fault
- Needs to demo on the FTP cycle OR If CID cannot be run on an FTP due to the MDS schedule, an alternate demo on the Unified Cycle can be done
- 1 cylinder/bank is required for the demo (pick the worst case cylinder for emissions for the demo)
- In-Use Ratio Monitoring compliant

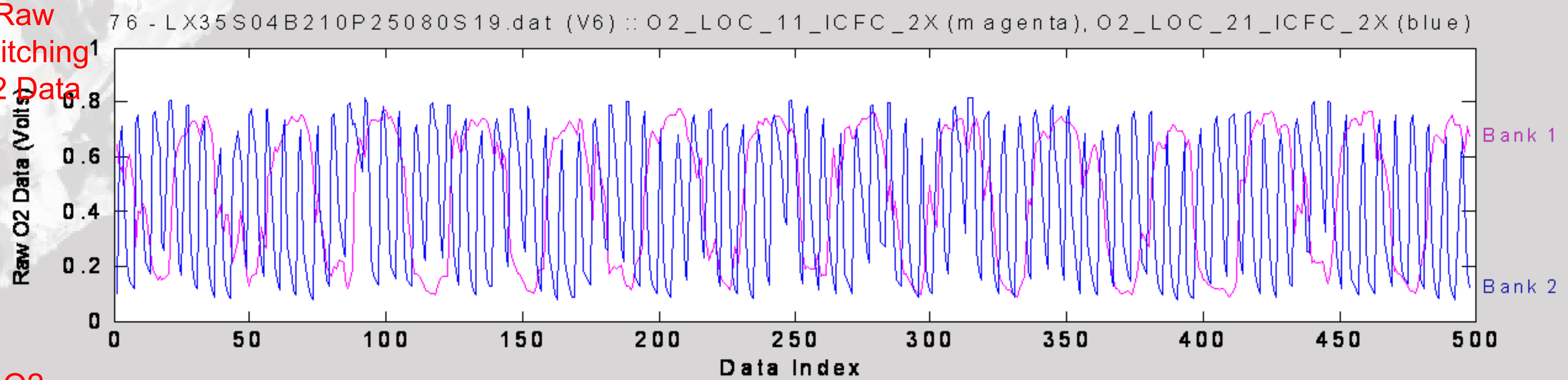
Cylinder Imbalance Diagnostic Monitor System



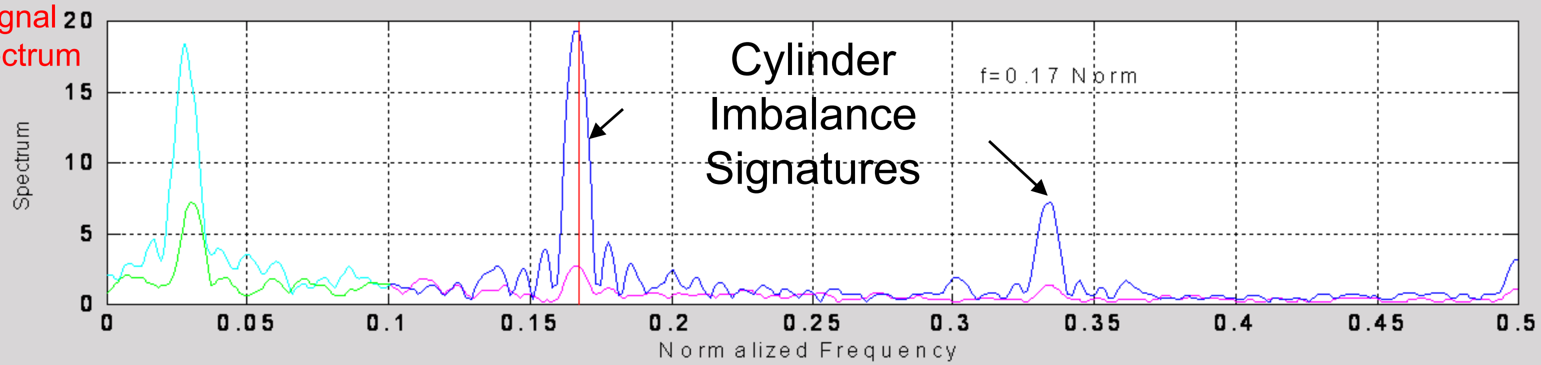
Cylinder Imbalance Detection Method #2: Detection Without Fuel Correction

- Method attempts to detect cylinder imbalance using the crank-angle-based signal content of the O_2 sensor compared to a reference signal.

Raw Switching O2 Data



O2 Signal Spectrum

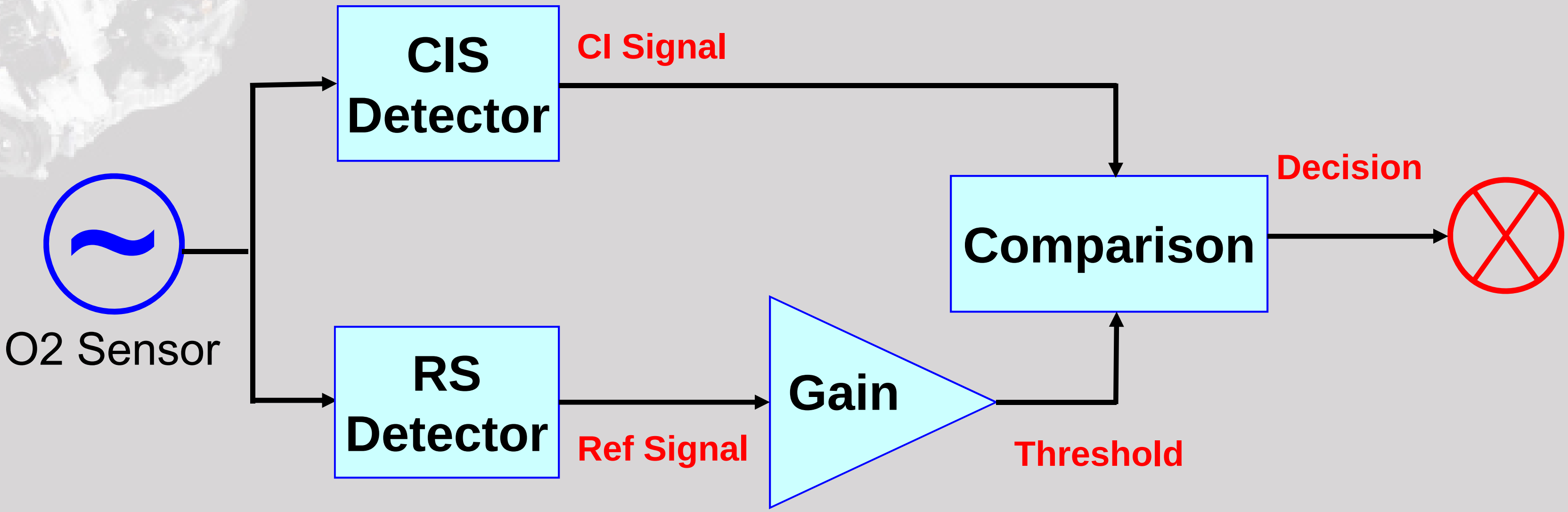


Cylinder Imbalance Detection Method #2: Detection Without Fuel Correction

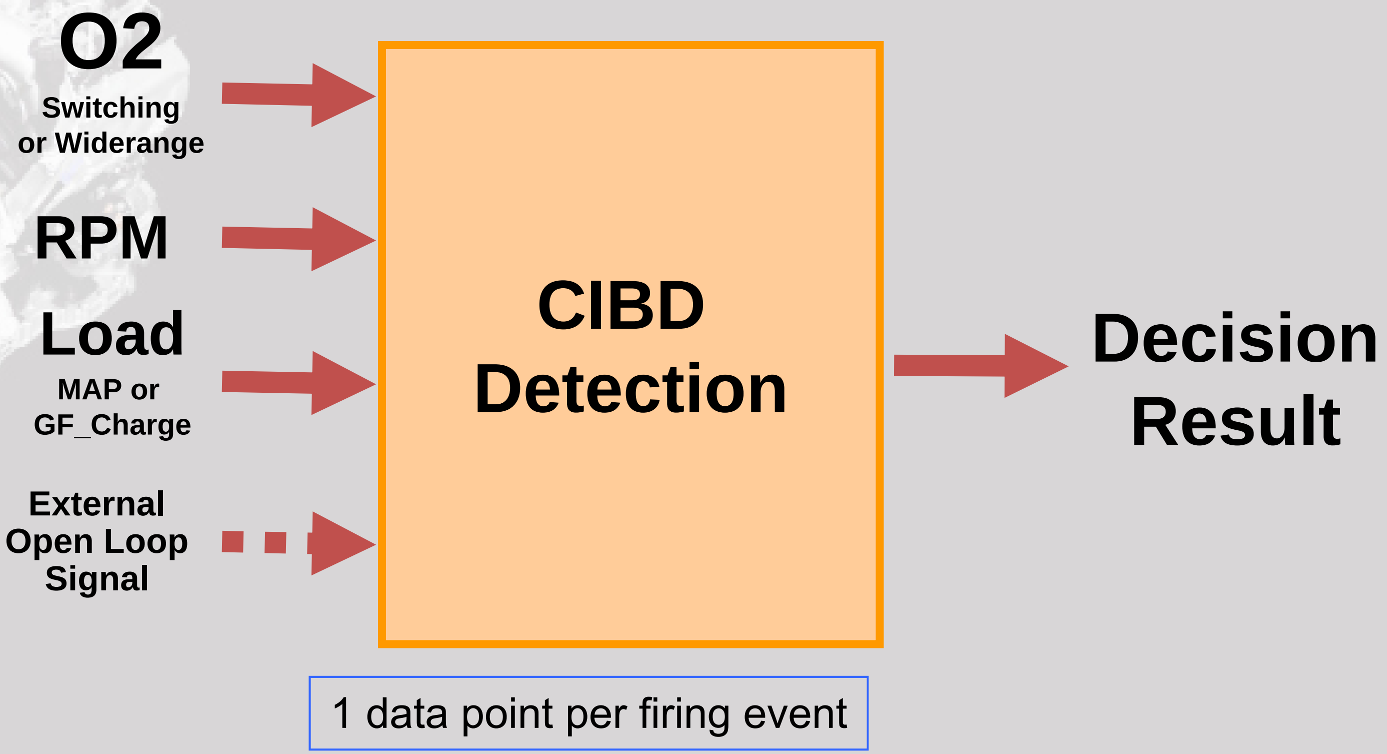
- Previous slide shows 2 graphs:
  - The first graph is the Bank1 and Bank2 O_2 sensors signals
  - Bank 1 is in balance, Bank 2 is imbalanced
  - The second graph is the same data viewed using the frequency domain with respect to crank-angle
- Method 2 uses the crank-angle based sampling technique to extract the amplitude versus frequency content of the O_2 sensors
- Method 2 compares the amplitude content of the cylinder imbalance frequency zone against the lower amplitude content of the reference zone

Cylinder Imbalance Detection Method #2: Detection Without Fuel Correction

- Method attempts to detect cylinder imbalance using the crank-angle-based signal content of the O_2 sensor compared to a reference signal.

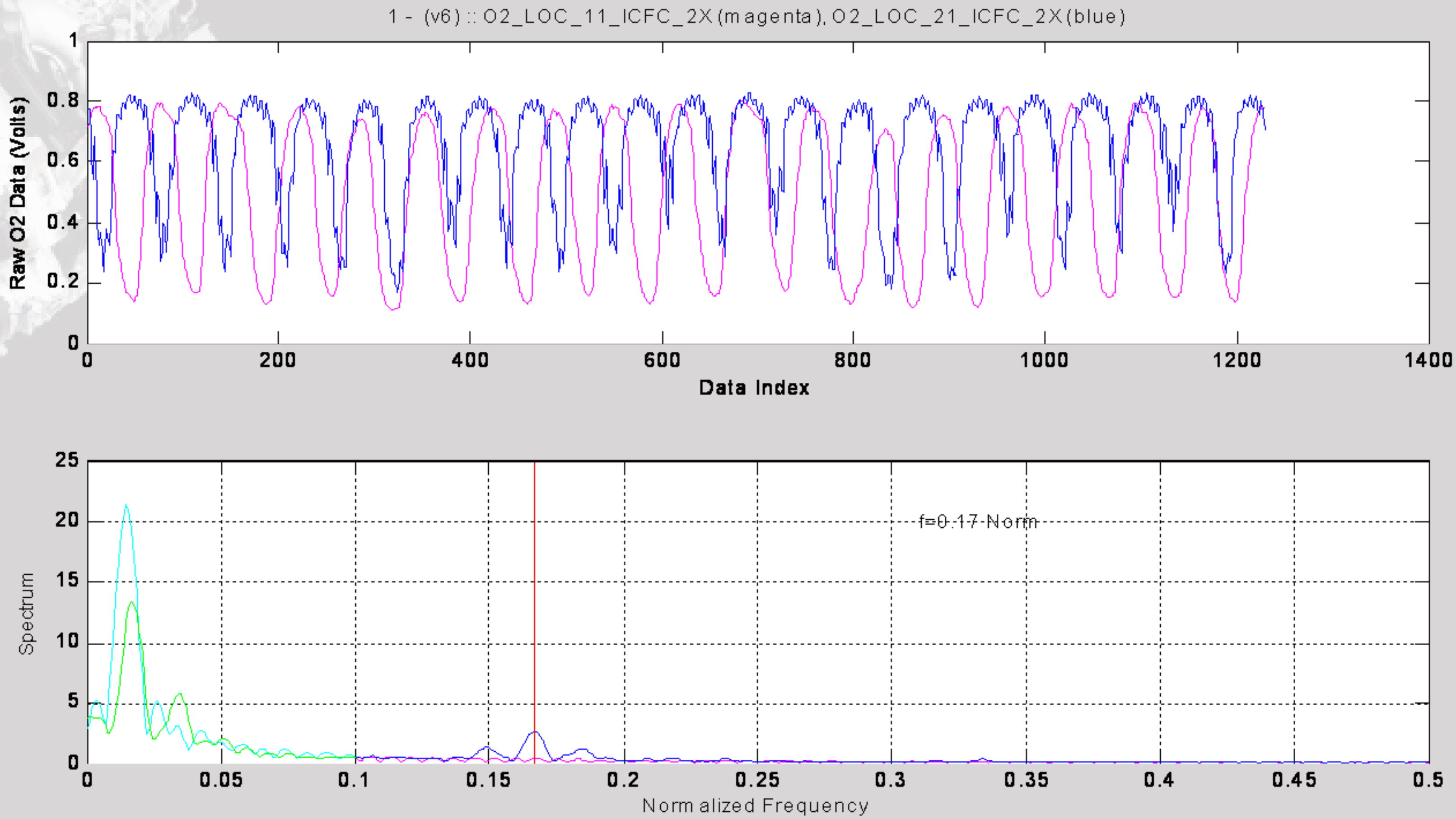


Input Signals and Data Sampling Requirement



Cylinder Imbalance Detection Method #2: Detection Without Fuel Correction

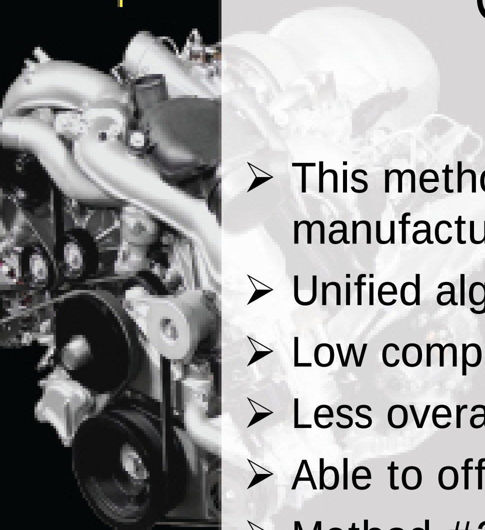
- Method #2 improves the detection with aged sensors.



Cylinder Imbalance Detection Method #2: Detection Without Fuel Correction

- Previous slide shows 2 graphs:
  - The first graph is the Bank1 and Bank2 O_2 aged sensors signals
  - Bank1 is in balance, Bank2 is imbalanced
  - The second graph is the same data viewed using the frequency domain with respect to crank-angle

- Because Method 2 uses a comparison of the imbalance region compared to the reference region, it improves our ability to detect cylinder imbalance with aged sensors.



Cylinder Imbalance Detection Method #2: Detection Without Fuel Correction

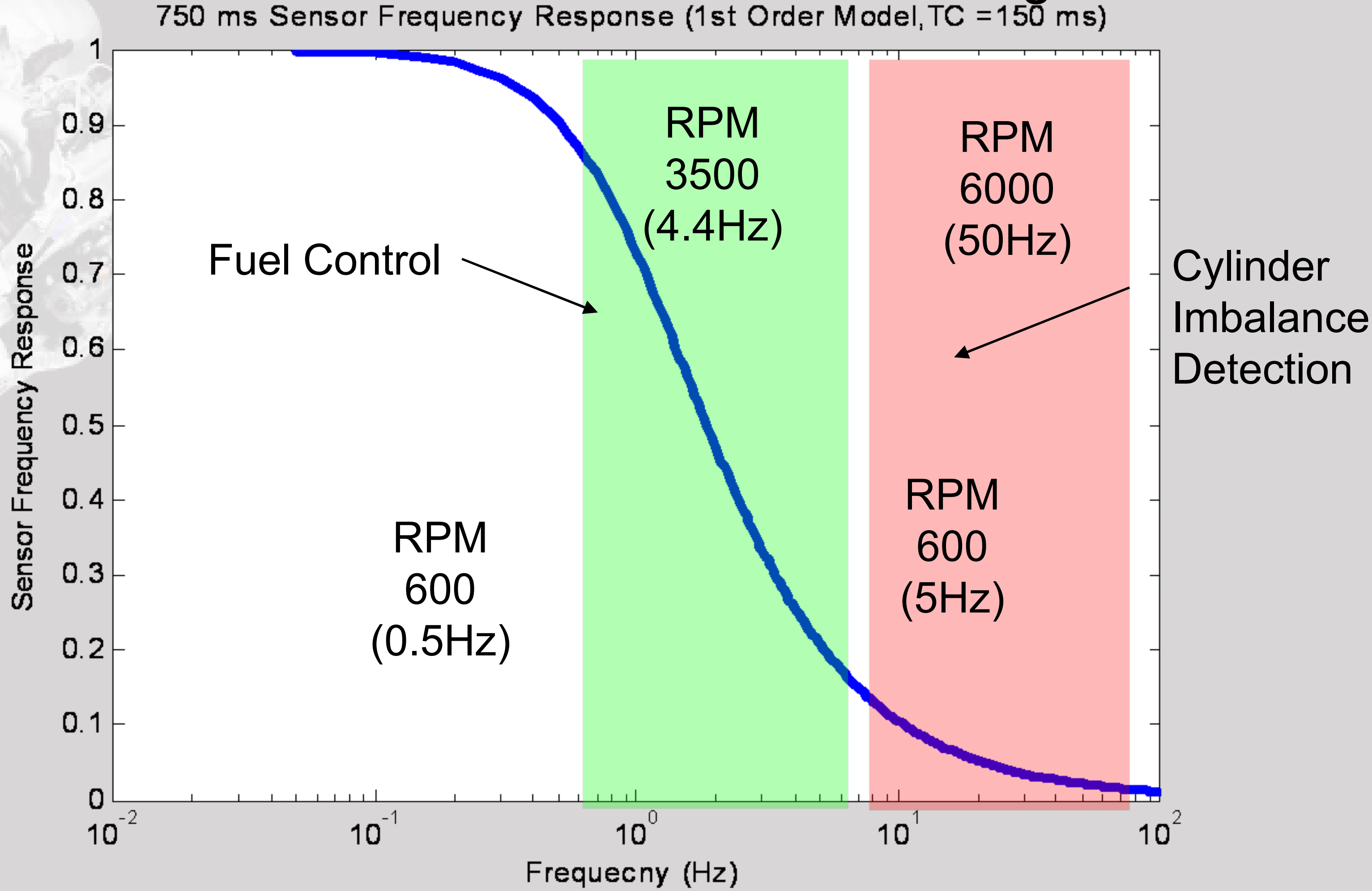
- This method allows us to detect imbalance in a larger range of O_2 sensor manufacturing tolerances and aging affects than Method #1
- Unified algorithm structure for different engines (I4 to V8)
- Low computation requirement and easy implementation
- Less overall calibration efforts from O2 sensor output to detection output
- Able to off-line process for calibration and evaluation
- Method #2 works in both closed loop and open loop fuel-air control conditions as well as transient conditions
- Sharing same algorithm for switching and wide range sensors
- Completed, standalone and passive monitor (no interference to other systems)
- Shorter monitor response time (no extra control-caused response time such as Method #1)
- Full range detection capable
- Independent to individual cylinder fuel control
- No base fuel calibration related calibration required.

Cylinder Imbalance Detection
Present Investigations

We are studying the monitor response to noise factors such as:

- Variable Valve Timing Cam Set-point or Control
- MDS
- Turbo charging
- PZEV
- other noise factors...

Required Frequencies for Fuel Control vs. Cylinder Imbalance Detection for a V6 Engine

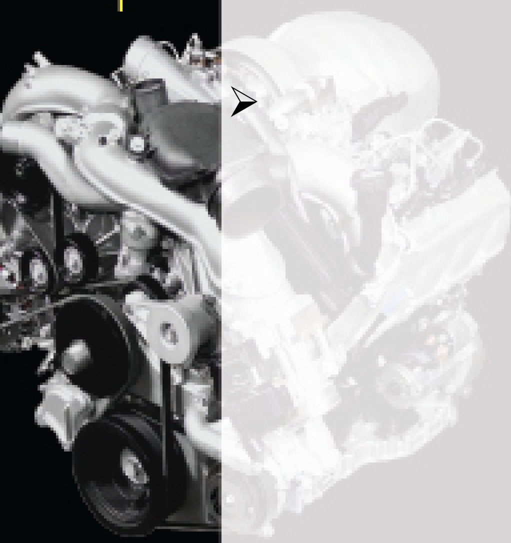


O2 Sensor Frequency Range For Fuel Control And For Cylinder Imbalance Detection

Previous slide shows the frequency response of a nominal bank O_2 sensor as modeled as a 1st-order system with a time constant of 150ms

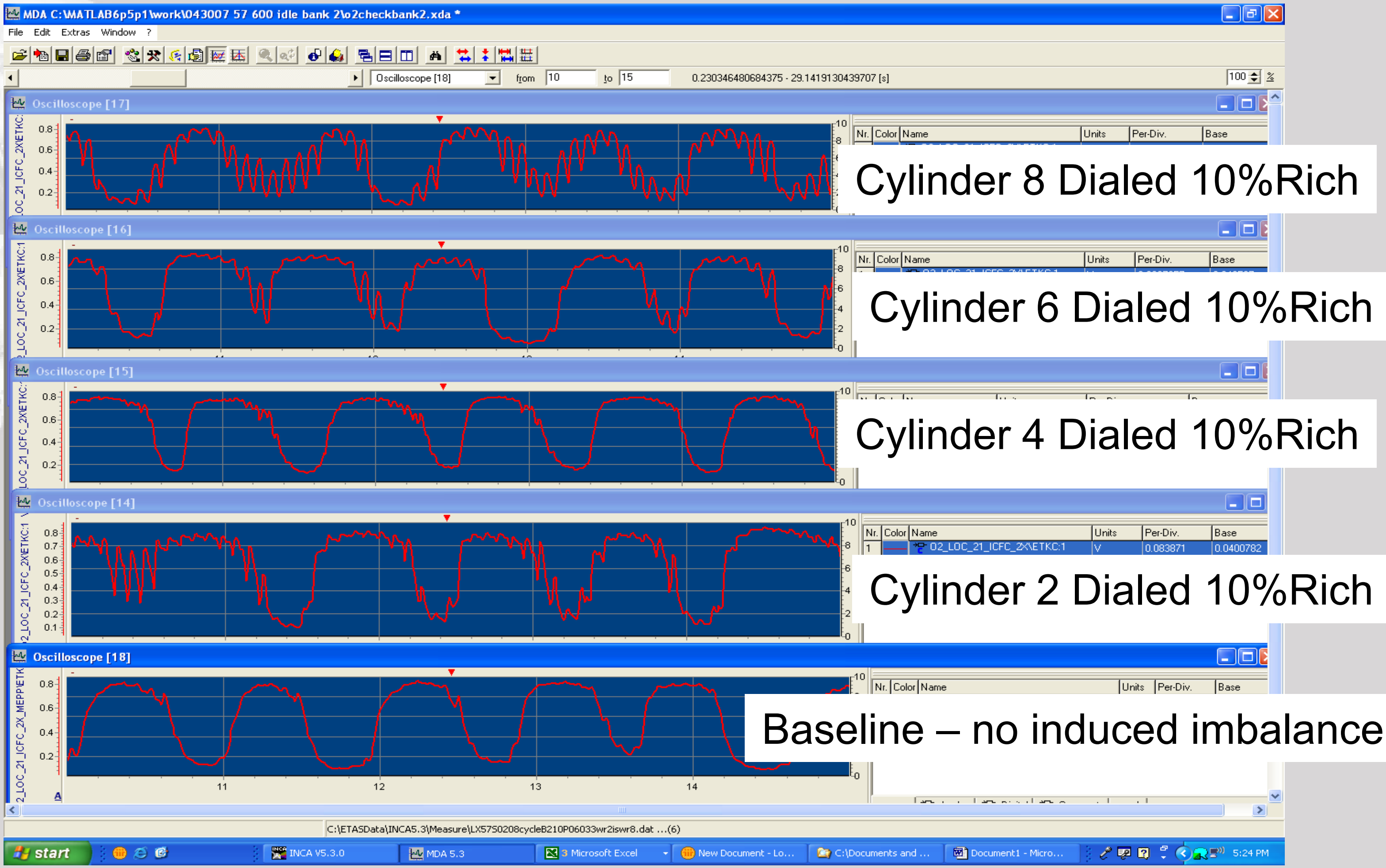
- The required frequency range for closed loop fuel control is shown in green with 600 RPM at 0.5 Hz and 3500 RPM at 4.4Hz

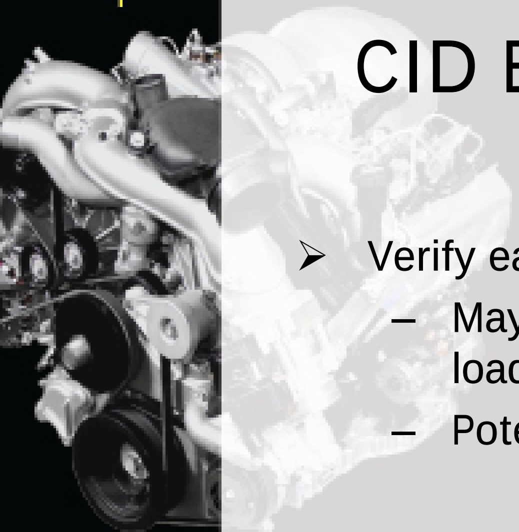
- The required frequency range for cylinder imbalance detection is higher than that of closed loop fuel control



Hardware Considerations

Upstream O2 sensor must be able to “see” each cylinder





CID Exhaust Manifold Design Requirements

- Verify each cylinder can be “seen” by US O2.
  - May require dyno test procedure (dial each cylinder at various speed / loads, analyze the high frequency component of O2 sensor)
  - Potential blind cylinders on some applications
- Good “mixing” manifolds increase emission robustness
  - Dialed >30% imbalance on V-6 XX-Body, still met emissions
  - Different Manifold, same engine. YY-Body exceeds emissions standard with 3% imbalance
- Good EGR, purge, O2 sensor placement

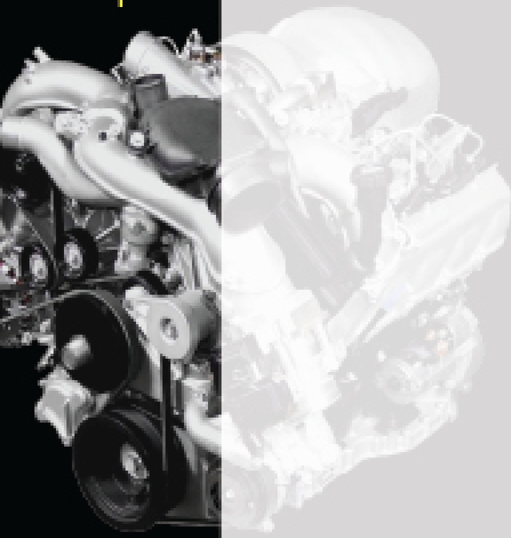
Calibration Process Overview

- Cylinder Blindness Testing
  - Same testing as Base Engine Cal, just High Frequency Imbalance Data Collected

- Data collection and calibration
  - Performance dynamometer acceptable for this

- Determination of worst case cylinder
  - Dynamometer development
  - Each cylinder dialed 10% rich and lean until worst emissions determined

- Evaluation of emissions threshold for target cylinder
  - Target cylinder dialed 4%, 8%, 12%, 16%, 20% until phase in threshold reached
  - Rich and Lean tests are necessary
  - On Dynamometer



DFMEA and Six Sigma

DFMEA Status

- CIBD has identified approx 60 failure modes at this time under the following headings
  - Enabled when it should be Disabled
  - Disabled when it should be Enabled
  - False Failure
  - False Pass
- Highest RPN identified is 200 under the failure mode of "Poor exhaust flow distribution at sensor location"
  - RPN should reduce once a CFD study is completed and leads to new process of locating O2 sensors for maximum CID effectiveness
  - Cylinder blindness tests also used as Design Control – Prevention

Design for Six Sigma (DFSS)

- Cylinder Imbalance Diagnostics was reviewed and determined to be a "Robust Assessment"
  - Two methods of diagnostics were created and will be evaluated statistically for which method provides the least risk for false failure and false passing
  - Classified Attribute method recommended to be applied to this assessment with Standardized SN for detailed analysis

Design for Six Sigma (DFSS)

Design Concepts
Detection Method (ICFC or CIBD)

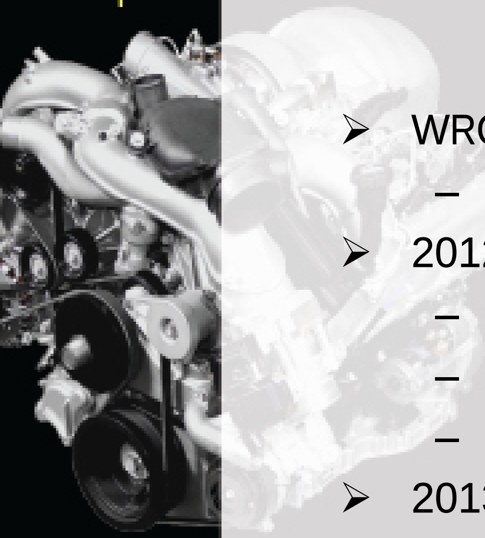
Input Signal
M: Deviation from stoichiometric fuel-air ratio

System
Cylinder Imbalance Detection Algorithm

Output Response
y: ICFC: Cylinder fuel-air multiplier
y: CIBD: Cylinder imbalance ratio

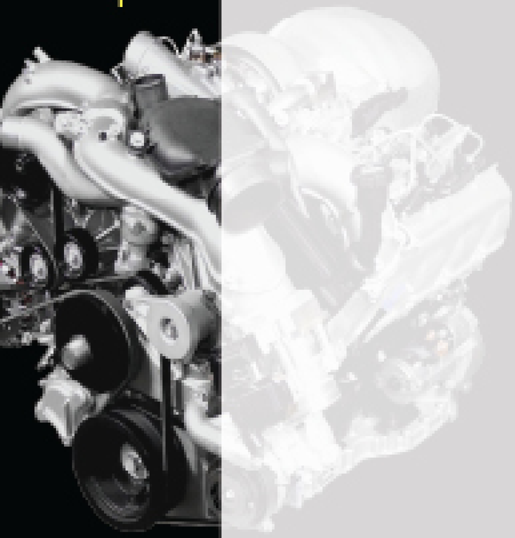
Noise Factors
O2 Sensor Aging (new and aged)
O2 Sensor Penetration (Boss Length)
Exhaust Backpressure
Closed Loop Enable Delay (2 levels only)
VE Adaptive Cell Ramping (-10% shift, +10% shift)
Purge Amount (full load, no load)
Cam Response (slow, fast)
Fuel Type (E85, E0)
Accelerated Enrichments (AE)s (nominal, high)

Symptoms of Poor Performance
Excessive Emissions
Engine Stumble
Engine Stall



Future Considerations

- WRO_2
  - Diagnostic vehicle under development
- 2012MY
  - MDS - DFSS
  - Flow Control Valve – DFSS
  - PZEV
- 2013MY
  - CVVL
  - Turbo - data already reviewed , capability OK
  - DI – Diagnostic data collection scheduled



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