Air-Fuel Ratio Cylinder Imbalance Monitoring

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(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 O₂ sensor responses
  - Select the cylinder that has the largest impact on the O₂ 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
O₂ Responses (New Sensor)

- Dial 10% imbalance at warm idle
- O₂ signal becomes noisier when cylinder imbalance exists
O₂ Responses (500-mile Sensor)

- Trend is more obvious as sensor ages further
- Statistically, cylinder 4 shows biggest impact on O₂ response, and was thus selected as test cylinder
Test-Averaged CVS Total Tailpipe Emissions

4-test average for each category

<table>
<thead>
<tr>
<th></th>
<th>C80</th>
<th></th>
<th>HWy</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NMHC</td>
<td>CO</td>
<td>NOx</td>
<td>NMHC</td>
</tr>
<tr>
<td>30% L</td>
<td>0.6%</td>
<td>81.7%</td>
<td>43.5%</td>
<td>-45.4%</td>
</tr>
<tr>
<td>10% L</td>
<td>25.7%</td>
<td>69.8%</td>
<td>15.4%</td>
<td>-2.6%</td>
</tr>
<tr>
<td>BASE</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
</tr>
<tr>
<td>5% R</td>
<td>-25.3%</td>
<td>-5.0%</td>
<td>38.1%</td>
<td>-50.0%</td>
</tr>
<tr>
<td>6.5% R</td>
<td>-35.2%</td>
<td>-16.5%</td>
<td>168.6%</td>
<td>-61.0%</td>
</tr>
<tr>
<td>10% R</td>
<td>-29.7%</td>
<td>-11.7%</td>
<td>321.8%</td>
<td>-56.8%</td>
</tr>
</tbody>
</table>

lower NMHC & CO, much higher NOx;
Different NMHC trends:
Hwy: drops, C80: goes up then falls down
higher CO & NOx;
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:**
  - 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
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)
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 O2 Control, should be able to remove the imbalance to some extent.
Chrysler Monitoring Requirements
<table>
<thead>
<tr>
<th>Monitoring Requirements</th>
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</thead>
<tbody>
<tr>
<td><strong>Air-Fuel Ratio Cylinder Imbalance</strong></td>
</tr>
<tr>
<td><strong>MIL (Malfunction Indicator Lamp) requirement when either condition is met</strong></td>
</tr>
<tr>
<td><strong>Demonstration Reporting</strong></td>
</tr>
<tr>
<td><strong>Legislative Diagnostics</strong></td>
</tr>
<tr>
<td><strong>Rate Based Monitoring</strong></td>
</tr>
</tbody>
</table>
# Rate Based Monitoring

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

<table>
<thead>
<tr>
<th>Global disable conditions</th>
<th>Common disable conditions CARB accepts for many diagnostics with approval</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>- Below 20 degrees F</td>
</tr>
<tr>
<td></td>
<td>- Above 8,000 feet in elevation</td>
</tr>
<tr>
<td></td>
<td>- Battery Voltage below 11.0 volts</td>
</tr>
<tr>
<td></td>
<td>- Fuel level less than 15 %</td>
</tr>
<tr>
<td></td>
<td>- With PTO engaged</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Other disable conditions</th>
<th>Cylinder Imbalance Monitor is not required to run when:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>- Any signal used as an input has a failure</td>
</tr>
<tr>
<td></td>
<td>- During a driving condition that may cause a false pass or false fail situation</td>
</tr>
</tbody>
</table>

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 J 1979 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 O₂ sensor has not failed
- Fuel Trim and Fuel System monitors have not failed
- Misfire monitor has not failed
- No injector faults, knock faults, O₂ 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 O₂ 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
Cylinder Imbalance Detection Method #1: Cylinder Imbalance Detection with Fuel Correction

O2 signal with Induced Cylinder Imbalance Before Correction

Cyl 1 Adaptive Goes lean
Cyl 2 Adaptive Goes rich
Cyl 3 Adaptive Goes lean

O2 signal After Imbalance Correction

Bank 2 Step Response with ±5% Bias

Cyl 1
Cyl 2
Cyl 3
Cylinder Imbalance Detection Method #1: Cylinder Imbalance Detection with Fuel Correction

Previous slide shows an example of a bank O₂ 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 O₂ 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 850 ms.
- \( O_2 \) monitor must detect an 850 ms 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

O₂ Control

O₂ Sensor

Cyl 1

Cyl 2

Cyl 3

Cyl 4

stoich

stoich

stoich

5% R

1.25% R overall

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

- **Data Inputs**
- **CIBD Detection**
- **CID Bookkeeping**
  - Configuration
  - Enablers, Inhibitors
  - Fault Processing
- **Task Management**
- **Intrusive Fuel Dialing**
- **MIL**
Cylinder Imbalance Detection Method #2: Detection Without Fuel Correction

- Method attempts to detect cylinder imbalance using the crank-angle-based signal content of the O₂ sensor compared to a reference signal.
Cylinder Imbalance Detection Method #2: Detection Without Fuel Correction

- Previous slide shows 2 graphs:
  - The first graph is the Bank1 and Bank2 O₂ 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 O₂ sensors

- Method 2 compares the amplitude content of the cylinder imbalance frequency zone against the lower amplitude content of the reference zone
Method attempts to detect cylinder imbalance using the crank-angle-based signal content of the O₂ sensor compared to a reference signal.

Cylinder Imbalance Detection Method #2: Detection Without Fuel Correction

- Method attempts to detect cylinder imbalance using the crank-angle-based signal content of the O₂ sensor compared to a reference signal.
Input Signals and Data Sampling Requirement

- O2 (Switching or Widerange)
- RPM
- Load (MAP or GF_Charge)
- External Open Loop Signal

CIBD Detection

Decision Result

1 data point per firing event
Method #2 improves the detection with aged sensors.

Cylinder Imbalance Detection Method #2: Detection Without Fuel Correction

1 - (v6) : 02_LOC_11_ICFC_2X (magenta), 02_LOC_21_ICFC_2X (blue)
Cylinder Imbalance Detection Method #2: Detection Without Fuel Correction

- Previous slide shows 2 graphs:
  - The first graph is the Bank1 and Bank2 O₂ 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 O₂ 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

750 ms Sensor Frequency Response (1st Order Model, TC = 150 ms)

- RPM 600 (0.5Hz)
- RPM 3500 (4.4Hz)
- RPM 6000 (50Hz)

Fuel Control

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

Previous slide shows the frequency response of a nominal bank O₂ 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

Cylinder 8 Dialed 10% Rich
Cylinder 6 Dialed 10% Rich
Cylinder 4 Dialed 10% Rich
Cylinder 2 Dialed 10% Rich
Baseline – no induced imbalance
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
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)

**Input Signal**
- M: Deviation from stoichiometric fuel-air ratio

**Design Concepts**
- Detection Method (ICFC or CiBD)
- Cylinder Imbalance Detection Algorithm

**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)

**Output Response**
- ICFC: Cylinder fuel-air multiplier
- CiBD: Cylinder imbalance ratio

**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
Contact

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