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Individual Cylinder Fuel Control for Imbalance Diagnosis

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James C. Smith, Charles W. Schulte and David D. Cabush
Delphi Corp.

ABSTRACT

This paper identifies a select method for performing cylinder imbalance measurement, correction and diagnosis. The impetus is to address new U.S. Federal regulations that require the detection of excessive cylinder air-fuel ratio (AFR) imbalance, and doing so requires the foundational ability to measure and preferably remove cylinder imbalance via active closed-loop control. This function is called Individual Cylinder Fuel Control (ICFC).

ICFC starts by extracting cylinder-imbalance information from the front oxygen sensor, and that information comes in the form a of continuous data stream. That stream is then parsed to create virtual sensors- one for each cylinder. Each virtual sensor acts as an imbalance or error signal which ICFC uses to correct and learn via feedback and feed-forward control for each cylinder.

The cylinder imbalance diagnostic is enabled by the presence of ICFC. The diagnostic continuously monitors to determine if ICFC is operating within its control authority, or if sufficient imbalance may exist to exceed a multiple of the applicable FTP emissions standard. Implementation of the diagnostic adds a subcategory to our existing Fuel System Diagnostic structure and reuses the common function-calling and accounting mechanisms to satisfy all of the fuel system monitoring requirements.

INTRODUCTION

ICFC has been openly reported on since the latter 1990's [1, 2]. There are two basic definitions of cylinder imbalance, with the first being in terms of AFR and the second, torque. This paper addresses AFR imbalance expressed in terms of equivalence ratio ϕ (Eq. 1) which is preferable from a control system design standpoint since the control input is fuel, not air.

$$\phi = \frac{1}{\lambda} = \frac{(F/A)}{(F/A)_{stoich}}$$

Eq. 1

Cylinder imbalance is not only affected by fuel injector inconsistencies, but also by maldistribution in fresh-air intake, exhaust-gas recirculation (EGR) and canister purge vapor, to name a few. Variation in fuel delivery occurs mainly to injector flow variation, but may also occur due to improper management of pressure pulsations inside the fuel rail. Therefore attempting to solve imbalance issues solely by making perfectly matched injectors would not solve the problem, but it would add significant cost. Conversely, designing an intake system that balances fresh air, EGR, PCV and purge vapor across all engine operating conditions would be extremely challenging, if not impossible in most applications. Also, due to the infinitely variable nature of EGR percentage and the fraction of cylinder fueling due to canister purge vapor, attempting to compensate for cylinder ϕ imbalance using fixed, open-loop offsets would be typically futile. In addition, non-design related faults could occur such as a manifold leak or variable cam lift malfunction. Therefore active feedback control is required.

Such feedback can be provided by the front (pre-catalyst) oxygen sensor, and in today's market that sensor could either be a non-linear “switching” sensor or a wide range air-fuel (WRAF) sensor which are piecewise-linear. Switching sensors are less costly than WRAF sensors, but for various reasons manufacturers are equipping more and more vehicle platforms with WRAF sensors. Regardless of the sensor type selected, the control must be robust to sensor-response variation due to aging, poisoning and the like, and will serve as the foundation for the corresponding diagnostic.

Continually evolving California Air Resources Board (CARB) On-Board Diagnostic (OBD) regulations have introduced a requirement to monitor fuel system imbalance. The requirement is to be phased-in, beginning with 25% of the 2011 model year, then 50% in 2012, 75% in 2013 and 100% in 2014 and beyond. This new requirement was promulgated as an addition to the existing Fuel System Monitoring section of the regulation.

The diagnostic algorithm is required to detect an AFR cylinder imbalance due to cylinder-specific malfunctions. All such detection and correction of the net effect of these imbalance sources is ICFC, which is where our discussion will now begin.

INDIVIDUAL CYLINDER FUEL CONTROL

In 2000, Delphi tested its newest version of ICFC, which is now significantly more advanced than that reported on in [2]. One of the algorithm's major steps forward was found in the DSP portion operating on the oxygen sensor output, and unlike other reported ICFC efforts at that time, this algorithm used a switching oxygen sensor, and did so with excellent results. In the years since, the algorithm has been greatly honed, put into production, and also expanded to work well with a WRAF sensor. As seen in Fig. 1, the algorithm can be broken down into six main stages:

1. Data Extraction
2. Virtual Sensor Creation
3. Aligning Virtual Sensors with Cylinders
4. Feedback Imbalance Correction
5. Feed-Forward Learning
6. Mode Control

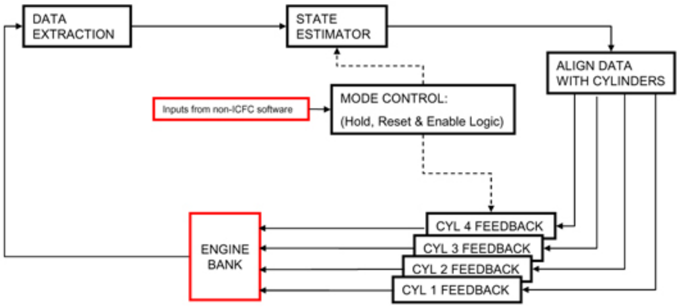

Figure 1. The structure of the ICFC algorithm.

ICFC STAGE 0: DATA ACQUISITION

There is a key portion of ICFC that lies outside of the algorithm, and that is the data acquisition of the oxygen sensor signal by the engine control module. The first consideration is the sensor itself. It must have sufficient bandwidth to report cylinder-imbalance information, and it must produce an analog signal that can be sampled synchronously with engine firing events. Some WRAF sensors have electronic interfaces that only produce a sampled signal at a fixed update rate, and that will not suffice.

The second consideration is noise and anti-aliasing filtering. Due to the event-synchronous sampling, these are typically not dominant issues; however any analog electronic filter between the sensor and the analog-to-digital converter must have a high enough cut-off frequency so as to not attenuate the imbalance information.

Finally is sampling rate. Testing has shown that it is both necessary and sufficient to sample at twice the engine bank's maximum event rate, so that at least one sample is taken on each engine bank event and at least one sample lies midway between each engine bank event. For example, for a V6 which fires in a purely bank-alternating pattern, sampling every engine event would sample at twice the maximum engine *bank* firing frequency. However, for a 4-cylinder and V8, sampling would have to occur at twice the overall engine firing event rate to satisfy the stated sampling-rate criteria.

ICFC STAGE 1: DATA EXTRACTION

The first step in successfully running ICFC is to extract the imbalance information from each bank's front oxygen sensor. The solution chosen was to create an adaptive digital high-pass filter with coefficients that are RPM-dependent [3] due to the following requirements:

1. Sampling must be synchronous with cylinder events, therefore the *time* rate at which the filter executes is not fixed, but rather a function of engine speed, number of engine banks, number of cylinders per bank and bank-to-bank firing order type.

2. The filter cut-off frequency must change with RPM since the cylinder-imbalance frequency and average fuel-control toggling frequency both scale with engine speed. Therefore separating the two cannot be achieved effectively using a fixed continuous-time, cut-off frequency.

This filter removes the lower frequency content as best as possible, with minimal or no attenuation of the imbalance information (previously referred to by many as "noise"). The typical action of this Data Extraction Stage is shown in Fig. 2. The input to the filter is the oxygen sensor signal sampled on an engine-event basis as just stipulated. The resulting output is a data stream that contains only cylinder-imbalance information with the DC bias and lower frequency rich-lean toggling removed.

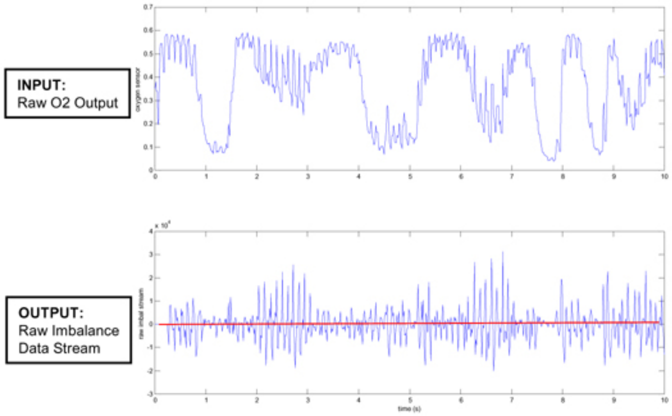

Figure 2. The Data Extraction Stage's action on the raw oxygen sensor output.

ICFC STAGE 2: VIRTUAL SENSOR CREATION

The adaptive high-pass Data Extraction filter provides a *stream* of raw imbalance information; however running ICFC requires separate imbalance signals for each cylinder. Each signal is the error term upon which the individual control loop is closed since they report the amount each cylinder is rich or lean with respect to the bank's average. Therefore this raw data stream must be mathematically parsed into multiple virtual sensor signals - one for each sample location in the engine cycle.

A key contribution of [1] was the mathematical construct shown in Eq. 2, which formulated a state estimator whose states were the cylinder imbalance values. In this equation, $\Delta\phi$ is a vector of cylinder imbalance values, u is the raw imbalance stream, and y is the oxygen sensor output. As Eq. 2 stands, it is nothing more than a numerical carousel that updates each state once per engine cycle from the raw imbalance data stream, and then applies a first-order low-pass filter ($0>g>1$) to remove noise on that state. Noise-removal filtering cannot be applied until after the imbalance data stream is parsed into individual signals, or otherwise it would remove or smear individual cylinder information, which is completely unacceptable.

The theory behind this state-space construct is that cylinder gas-mixing characteristics can be modeled by altering the **process**, **input**, and particularly the **output** matrices to show that the oxygen sensor's output can be a sole function of the currently exhausting cylinder, or be a smeared function of the currently exhausting cylinder and one (or ones) previous to that. The output equation in Eq. 2, as shown, is for the former case, but if the **output** matrix were altered to have non-zero values in components other than in the first position, this would represent gas mixing worthy of modeling.

$$\Delta\hat{\varphi}(k+1)=\begin{bmatrix} 0 & \dots & 0 & g \\ & & & 0 \\ & \mathbf{I}_7 & & \vdots \\ & & & 0 \end{bmatrix}\Delta\hat{\varphi}(k)+\begin{bmatrix} (1-g) \\ 0 \\ \vdots \\ 0 \end{bmatrix}\cdot u(k)$$

$$y(k)=\begin{bmatrix} 1 & 0 & \cdots & 0 \end{bmatrix}\Delta\hat{\phi}(k)$$

Eq. 2

ICFC STAGE 3: ALIGN VIRTUAL SENSORS WITH CYLINDERS

Once the virtual sensor signals have been created, they must be aligned with the cylinders. This is achieved with a series of open-loop tests that in turn produce fixed calibrations for open-loop assignments. The open-loop tests involve imposing square-wave perturbations on the first two cylinders in a given engine bank's firing order. Both square waves have a period of 10 seconds and amplitude of +/-0.05 ϕ, but are 180° out of phase with respect to each other, thereby creating markers in the cylinder imbalance data that allow the calibrator to visually identify which virtual sensor contains the imbalance data for which cylinder. This test results in a series of plots shown in Fig. 3, where in each plot the square wave imposed on the first cylinder is plotted along with the imbalance information from the virtual sensor. The goal is to then locate the plot or virtual sensor that shows the strongest sympathetic response to the perturbation, followed two virtual sensors later by the opposite response, since that is how the perturbations are imposed on the fuel injectors.

In Figure 3 we can see that Virtual Sensor 4 responds in-synch with the perturbation imposed on the first cylinder, and that two positions later we see the opposite response on Virtual Sensor 6. We also see another such pair in Virtual Sensors 5 and 7. The signal strength on both pairs are comparable, so to align the virtual sensors with the cylinders in that bank, an indexing offset of 4 or 5 is applied. Also note that in each plot there are two signal traces: red and green. Red is the raw parsed information straight from the imbalance data stream. The green trace is the low-pass filtered one coming out of the state estimator in Eq. 1.

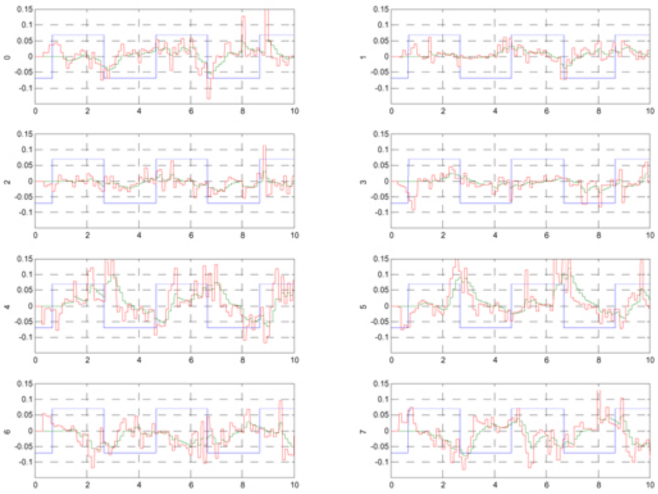

Figure 3. Aligning virtual sensors with an engine bank's cylinders.

ICFC STAGE 4: FEEDBACK IMBALANCE CORRECTION

Once the imbalance information is 1) extracted from the front oxygen sensor, is then 2) parsed into individual virtual sensors, and then 3) aligned with the proper cylinders, the task of removing the imbalance via feedback control is now relatively straightforward. Fig. 4 shows how ICFC relates to well-known classical control law: a standard control loop is shown along the top, and the analogous ICFC control loop is shown beneath it.

The control law selected for ICFC was P.I. control with some important customizations, with the foremost being compensation for changes in the open-loop plant gain across engine operating conditions, mainly due to corresponding changes in oxygen-sensor dynamics. Additionally, an integral control loop acting on the average of a bank's final ICFC fueling multipliers was included to prevent ICFC from creating a net bias on a bank's fueling which would then fight with the overall or average fuel control for that bank. This is a subtle but very important inclusion to the design and must not be overlooked.

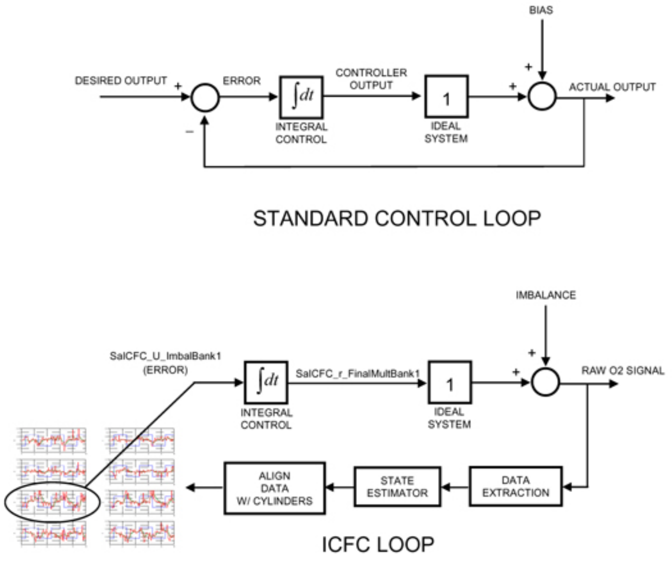

Figure 4. The ICFC feedback loop as compared to a standard feedback loop.

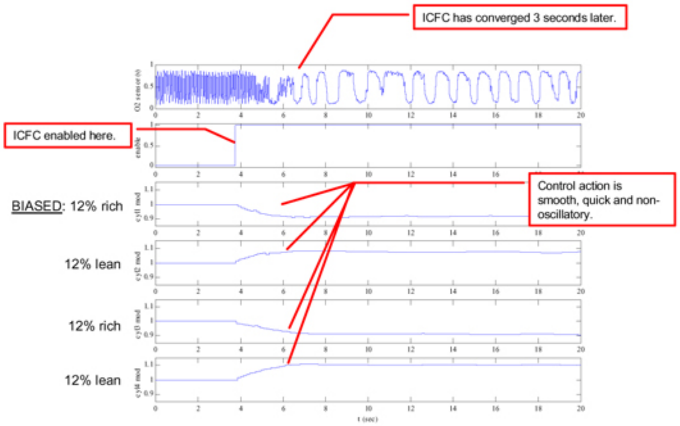

Figure 5. An example of ICFC's closed-loop step response. Convergence is fast and non-oscillatory, and achieved here in about 3 seconds once enabled.

ICFC STAGE 5: FEED-FORWARD LEARNING

As previously discussed, cylinder imbalance is created by both imbalance in injected fuel, and imbalance in gaseous intake (air, EGR, purge, etc.). It is for this reason that imbalance varies *across* engine operating conditions. For purge, both flow rate and fuel fraction can constantly be changing; and for fresh air, EGR and purge, cylinder distribution is a highly complex function of intake gas-flow dynamics.

Since imbalance can vary significantly as the engine traverses the span of its operating conditions, long-term feed-forward learning was added so that ICFC can rapidly adapt to changing sets of imbalance conditions. To do so, cylinder imbalance is measured by running ICFC in zones of engine operating points, and for each zone if any ICFC closed-loop correction has occurred during that visit, the final ICFC fueling multipliers are recorded as the engine leaves that zone so that when it returns, learning does not have to begin anew each time.

ICFC STAGE 6: MODE CONTROL

The final key portion of ICFC is not a feedback stage but rather a supervisory state machine. In it there are four states.

1. Reset ICFC
2. Run Closed Loop ICFC
3. Same-Zone Hold
4. Driven Into Authority Limit

State 1: Reset ICFC

Conditions are such that it is inappropriate to run the Data Extraction front-end, the parsing State Estimator, closed-loop feedback, or feed-forward learning. The three main conditions for putting ICFC into a reset mode are: 1) the engine is not yet warm; 2) the engine has just changed from one operating zone to another (the engine needs to be in a quasi semi-state condition so that imbalance is somewhat static); and 3) non-volatile memory has just been reset, thereby suddenly clearing out the feed-forward learned values.

State 2: Run Closed-Loop ICFC

Conditions are such that ICFC is allowed to run closed loop, meaning that the state estimator, feedback control and feed-forward learning are all enabled. Necessary conditions include: 1) the switching sensor is actively switching and not being pegged rich or lean, 2) engine conditions are such that the oxygen sensor can be reliably used to extract imbalance information, 3) the engine is steadily in the same operating zone, and 4) the final ICFC fueling multipliers are not being driven into their authority limits.

State 3: Same-Zone Hold

Conditions do not require a full reset. The oxygen sensor cannot be reliably used at this moment to provide cylinder-imbalance information. The engine is in the same zone of operation, but for various reasons the information being extracted from the oxygen sensor cannot be trusted for use in closed-loop correction. Therefore the feedback control is held, not reset, and the Data Extraction filter and State Estimator keep running until the issue clears up, or conditions call for an ICFC reset.

State 4: Driven Into Authority Limit

ICFC has been running closed loop, but at least one final ICFC fueling multiplier has hit the authority limit and is actively being driven into it. At this point feedback control action is held, but the state estimator is allowed to keep running to see if the error signal it produces changes sign so as to provide the opportunity for the system to naturally pull the offending cylinder out of the authority clip if conditions change.

CYLINDER IMBALANCE DIAGNOSTIC

The ICFC algorithm, as stated previously, is the foundation of this diagnostic that monitors whether ICFC is operating within its control authority limits. Implementation of this diagnostic has created a new subcategory within Delphi's existing Fuel System Monitoring structure; therefore this new addition to the Fuel System Diagnostic (FSYD) was given the abbreviation *FSYD_CI*.

ICFC is designed to divide the engine-operating space into distinct zones or cells currently based on engine speed (RPM) and intake Manifold Absolute Pressure (MAP) to apply a learned component of individual cylinder fuel trim. FSYD_CI will monitor the combined ICFC authority in each ICFC cell much like FSYD has for many years monitored similar cells for the engine's overall closed-loop fuel control; however the FSYD_CI arrays have an additional axis to monitor each cell for each *cylinder* individually.

ICFC fueling must be present, calibrated and operating for the Cylinder Imbalance diagnostic to function. Section E. 6.2.2 of the regulation [4] calls for detection of a malfunction when the adaptive feedback control has used up its available authority. Monitoring shall occur "*continuously for the presence of a malfunction*" (E.6.3.1) with provisions to define monitoring conditions under reasonably expected conditions in normal operation and during FTP cycles and at least once per driving cycle (D.3.1 and D.3..2) Our diagnostic implementation will be enabled continuously when the ICFC system is running closed loop (State 2) or would otherwise be running closed loop, except that it is currently being driven into its authority clip (State 4). An enable latch timer was added to the diagnostic's enable interface in the event that noise on the enable criteria prevents failure counts from accumulating quickly enough under certain circumstances. Fig. 6 highlights these features.

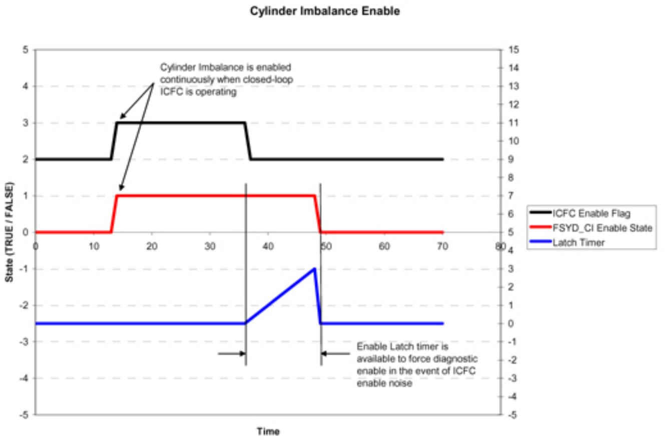

Figure 6. Illustration of the diagnostic enable state linked to ICFC operation.

As detailed earlier in this paper, ICFC's effect on fueling consists of three main components: (a) proportional and integral feedback with open-loop plant-gain compensation, (b) long-term learning in the form of adaptive feed-forward stored in the aforementioned RPM-MAP cells, and (c) average zeroing. All three components are combined and applied as per-cylinder fuel corrections to the final fuel-injector multipliers. The Primary Failure criteria flags will be set to TRUE when ICFC final multipliers exceed the boundaries set by ICFC or by the FSYD_CI sub-system as determined by sample and failure counters. There is currently no Secondary Failure Criteria for this subcategory to monitor.

The following illustration (Fig. 7) depicts an ICFC final output multiplier reaching its control authority limit. After a normal excursion timer expires, failure counts are accumulated until a threshold is reached at which point the failure flag is set to true. This is the recommended strategy for systems that have good fluid distribution characteristics and therefore have a modest amount of ICFC authority, e.g. +/-10% as in Fig. 7.

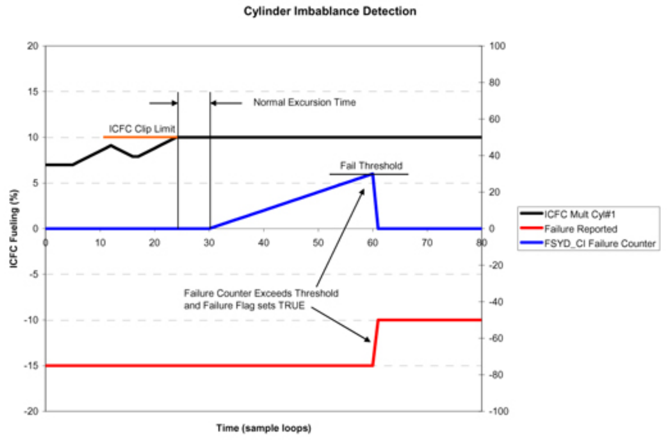

Figure 7. Cylinder imbalance detection upon loss of control authority

Some end users may opt to give ICFC larger control authority, and so it may be necessary to detect and report cylinder imbalance inside its limit in order to comply with the emissions multiple of the FTP standard for a given application. FSYD_CI has a separate internal threshold that may trigger a failure for this situation. Fig. 8 illustrates this strategy.

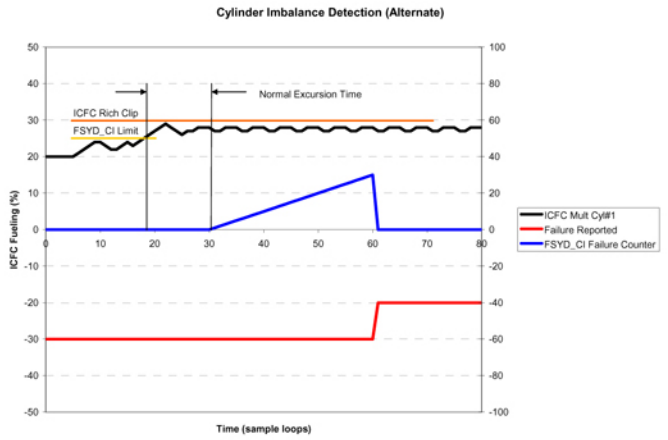

Figure 8. Cylinder imbalance detection without loss of control authority.

There are separate sample and failure counters for each cylinder and for each ICFC cell for each cylinder. For a six cylinder engine there will be a total of 48 positions in each array (6 cylinders *times* 8 ICFC cells per cylinder). Maximum excursion times track the total time failing in each cylinder for each cell and in both the rich and lean directions. For a V6, that creates a total of 96 positions in the array (6 cylinders *times* 8 ICFC cells per cylinder *times* 2 fault states - rich and lean).

Except as provided below, if a pending fault code is stored, the OBD II system shall immediately illuminate the MIL and store a confirmed fault code if a malfunction is again detected during either of the following two events: (a) the driving cycle immediately following the storage of the pending fault code, regardless of the conditions encountered during the driving cycle; or (b) on the next driving cycle in which similar conditions to those that occurred are re-encountered, for when the pending fault code was stored.

SUMMARY/CONCLUSIONS

The task of diagnosing excessive cylinder ϕ imbalance requires the ability to measure such imbalance. Here, Delphi has presented it production algorithms to perform both tasks. First, the function of our ICFC algorithm was broken down into six major components and the operation of each was explained. Our version of ICFC not only measures cylinder imbalance, but corrects it using closed-loop action. The algorithm begins by applying a high-pass adaptive filter to a single, front oxygen sensor (which may be either a switching or WRAF sensor). This produces a stream of imbalance information that is then processed into separate virtual oxygen sensors - one for each cylinder. These virtual sensors then act as individual-cylinder imbalance terms, and feedback control is then applied to drive those imbalances to zero. Long-term tabular feed-forward learning is also utilized. The final ICFC fueling multipliers then indicate the amount of relative imbalance for each cylinder, and it is this information that is used by the diagnostic.

The Cylinder Imbalance Diagnostic, which stands atop ICFC was also described in detail. CARB requires detection and reporting of Cylinder Imbalance beginning in model year 2011. The specific implementation adds a subcategory to the existing Fuel System Monitoring structure. This new diagnostic provides for detection continuously when closed-loop ICFC is operating, and it will detect and report a malfunction when ICFC is operating beyond its control authority or beyond a separate tighter cylinder imbalance limit if loss of emissions performance is detected.

REFERENCES

1. Ohata, A., Ohashi, M., Nasu, M., and Inoue, T., “Model Based Air Fuel Ratio Control for Reducing Exhaust Gas Emissions,” SAE Technical Paper 950075, 1995.

2. Kainz, J.L. and Smith, J.C., “Individual Cylinder Fuel Control with a Switching Oxygen Sensor,” SAE Technical Paper 1999-01-0546, 1999.

3. Smith, J. C., Kainz, J. L., *Individual Cylinder Air/Fuel Ratio Control Based on a Single Exhaust Gas Sensor*, US Patent US06382198B1, May 7, 2002.

4. Title 13, California Code Regulations, Section 1968.2, Malfunction and Diagnostic System Requirements for 2004 and Subsequent Model-Year Passenger Cars, Light-Duty Trucks, and Medium-Duty Vehicles and Engines (OBD II).

The Engineering Meetings Board has approved this paper for publication. It has successfully completed SAE's peer review process under the supervision of the session organizer. This process requires a minimum of three (3) reviews by industry experts.

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