Engine Polygraph®

Case History

2020-04-09

Idle & Load signature analysis on a
2003 Cadillac 3.0L V6 VVT DI engine
with over 150,000 miles.

Contents

Introduction: 3
- Spectral analysis of the waveforms: 5
- Cylinder segmentation and engine speed: 5
- Engine and Cylinder Features: 5
- Engine model data: 5
- Engine Polygraph hardware: 6
- Optional sensors to aid more precise diagnosis 6

Conclusions: 6
- Effects of rpm on the engine behavior and sense of 'integrity' 6
- Compression rings packed with carbon 6
- Misfire with fuel 6
- Possible head gasket weakness in one bank. 7
- Unexpected Oscillation in the Exhaust 7

The Engine and test conditions: 7

Assessment Methodology: 7
- Engine level parameters 8
- Cylinder level parameters 8
- The Scoring Models 9
  - Assessment Scores at idle 9
  - Model Graphic at Idle 9
  - The Points Graphic at Idle 11
  - The Profile Graphic at Idle 11
  - Scoring the Engine at Load 12
  - Model Graphic at Load 12
  - The Points Graphic at Load 13
  - The Profile Graphic at Load 14

Diagnostic Methodology 15
- Rules 15
- Abnormal Observations 16
- Engine Block Layout and Adjacency Matrix 16
- Cylinder Offset Diagram 17

The Diagnostics 18
- Diagnostics at Idle 18
- Diagnostics at Load 19

Future Work 19

Introduction:

Engine Polygraph® (EP), www.EnginePolygraph.com, is an application 'in the cloud' to store the FirstLook® sensor output from an ICE engine for future reference and optionally, to request an engine analysis report. An EP signature (Fig. 1) is a record of voltage from one or more piezoelectric sensors recording pressure changes (pulses) from an exhaust sensor and a crankcase sensor and optionally additional sensors at other locations on an internal combustion engine. The value to these signatures is that internal combustion engines repeat firing in the cylinders of the engine in a regular fashion. If everything is working well in the engine, the pulses repeat in very regular waveforms; however, engine problems usually present variations that repeat every engine cycle (two revolutions for 4-stroke engines).

The system is totally non-invasive, sampling and analyzing data by sampling the exhaust gas and the crankcase pressure through the oil dipstick.

There are a number of engine design features that must be considered when using EP, such as:

1. An engine with Cylinder Deactivation (also called Variable Displacement, Modulated Displacement, Active Cylinder Control, Multi-Displacement System, Dynamic/Active Fuel Management, among other names) will likely not be firing on all cylinders during a 'load' test. Running a test with only a subset of the cylinders active cannot identify any issues with the 'missing' cylinders. Most (if not all) of these engines use all cylinders at idle and so EP can be useful at idle for these vehicles. Some aftermarket manufacturers produce ECM 'dongles' that force the ECM to use all available cylinders. And so, engines with these can be tested at load. Engine models that have this feature are marked in our engine database if provided as a standard feature by the manufacturer. In such a case, the Diagnostic report will present a warning if you are running a load test.
2. A number of engines no longer have dipsticks and so there is no dipstick tube to provide access to the crankcase pressure. Perhaps one can use a modified oil filler cap or design a seal with orifice to obtain access.
3. Our engine database does not have all engines of the world loaded. If you can't find an Engine Model for the engine you are working with, find one as similar as possible and get the data. On the Engine data screen, you can make a comment describing what engine you really have. Please then send us a request to add your engine details, providing the engine model identification (name, displacement, number of cylinders and configuration and the date you ran the test to get the signature data).

The user may request an analysis (report) of the data in view of the engine model identified and parameters of the test conditions. Currently the report choices are Assessment, Diagnostic, or none. The Engine Polygraph® reports automate many of the steps that a user would perform manually in interpreting a 'signature': a pair of sensor waveforms from an internal combustion engine, one from the exhaust stream and the second from the oil dipstick tube.

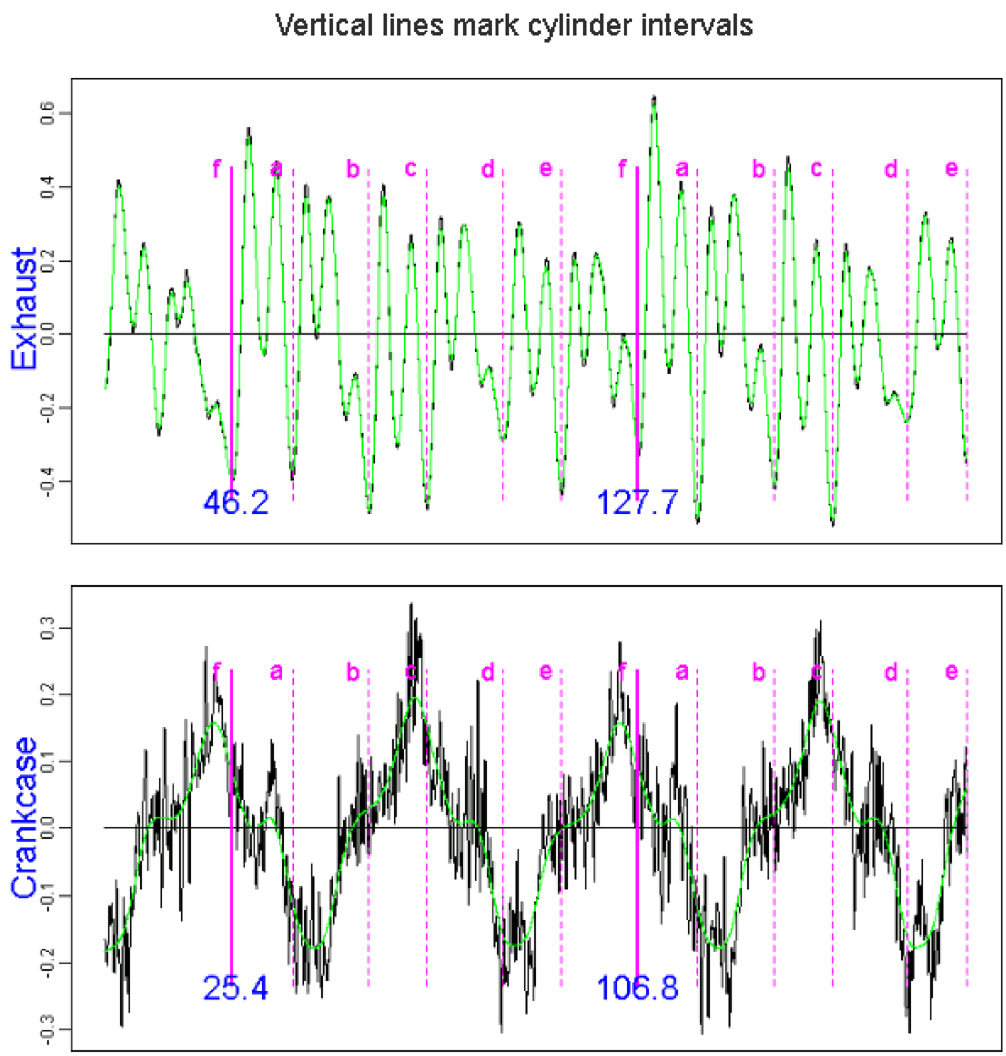


Fig. 1: A signature of a V6 engine running at 1473 rpm with the exhaust sensor sampling exhaust pressure at the end of the tailpipe and the crankcase vapor pressures from the oil dipstick tube.

Spectral analysis of the waveforms:

The piezoelectric sensors capture pressure variation at various locations on the engine with a very high frequency (over 20k Hz) so that the data can be analyzed in different parts of the spectrum to pick up pressure variations from various types of movement of different components. Flaws that appear once per engine cycle (all cylinders ‘fire’ only once - 720° in a 4-stroke engine) typically indicate a problem. Most noticeable variations are due to ‘cylinder’ functions that happen Ncyl times per cycle, where Ncyl is the number of cylinders. These changes are results of pistons, valves, etc. with a frequency of 75.2 Hz at 1500 rpm in a 6-cylinder engine. These are relatively smooth variations as each cylinder goes through their paces, producing the pressure changes resulting in the engine ‘hum’ that we hear. Things like bearings, timing chain links, etc. are much smaller and so produce higher frequency ’sounds’. Valves that have a little carbon preventing tight seal ‘whistle’ like a tea-kettle at a quite high frequency and an engine ‘knock’ from premature ignition gives off very high frequencies of very short duration.

Cylinder segmentation and engine speed:

Figure 1 shows the simultaneous exhaust and crankcase pressures (proportional to the displayed voltage) in firing order sequence. The green curves are the ‘pressure’ extracts from the raw voltage and the black is the raw voltage. The ‘black minus green’ is analyzed for higher frequency inferences. The solid red vertical lines are the boundaries for one engine cycle; the cylinder boundaries are obtained from the exhaust waveform. The blue numbers of the exhaust waveform are the timestamps in milliseconds at the start and the end of the engine cycle that has been selected for analysis; the numbers in the crankcase waveform are the millisecond times of the previous power stroke to help orient the crankshaft rotation. The accuracy of these boundaries depends on the initial estimate for the rpm that the user provides. If it is obvious that the derived values are wrong, one can use the web-based EP application to EDIT the signature information to update the value and re-submit it for an updated report. Read the FAQ document from the login page to get guidance on whether to increase or decrease the estimated rpm value.

Engine and Cylinder Features:

Engine level features are defined from data collected over the engine cycle: Vibrational intensity over the cycle in various spectral cuts, statistics over the pressures in each of the cylinder segments. A set of pre-defined features are calculated for each cylinder exhaust and crankcase to classify the waveform associated with each cylinder. The crankcase cylinders are defined based on the segmentation of the exhausts

Engine model data:

EP has a library of engine details, e.g. firing order, engine configuration, and the engine block layout. This data along with the simultaneous waveforms from the multiple sensors can provide significant insight about the operation of the engine being studied. Many engines are built with multiple ‘banks’ of cylinders and the engines might be mounted transverse or longitudinal (parallel to the direction of the vehicle motion) and that often affects the exhaust waveform in that the interference between the two exhaust streams from the manifolds at the crossover can interfere so that the cylinders from one bank have a different profile than those of the other bank.

Engine Polygraph hardware:

Predictive Fleet Technologies assembles, markets and distributes an **Engine Polygraph** kit and a laptop (PC) application to make the collection of engine signatures and the submission for storage and report generation easy and reliable. The kit is described in detail on the Predictive Fleet Technology website under the **Engine Polygraph > Products** tab. The PC application is called **EPReader** and it is documented in the ***EPReader Installation and User Guide*** available for download from the EP website.

Optional sensors to aid more precise diagnosis

There are a number of sensors that can be integrated with EP such as:

1. Current clamp to identify a specific cylinder (either the spark plug or an injector current)
2. Radiator cap with tap to measure coolant pressure with an additional piezoelectric sensor
3. High amperage current clamp for detecting starter current draw during cold-crank tests

This document describes the kinds of information that was obtained from the EP system

Conclusions:

The conclusions of the two tests indicate that the engine is running quite well now but does have some weaknesses that could result in significant repairs 'before long', depending on how much the engine is used in the future. At the current rate of under 5,000 miles per year, it might last a number of years. The engine appears to run better at highway speeds than in town and idling.

Effects of rpm on the engine behavior and sense of 'integrity'

The big surprise of the two tests at different rpms (idle and load) is that what appeared to be a significant problem at idle 'disappeared' when running at twice the rpm. It appears that at low rpm, reverse blow-by (flow of gases from the crankcase into a cylinder) can be significant at idle when the intake stroke takes twice as long as when the engine is running near highway rpm.

Compression rings packed with carbon

The Idle analysis of the Idle signature suggests that one cylinder has compression rings that appear to be constrained in their needed flexibility by carbon 'caking'. That shows up as a very big vacuum dip in the crankcase while the appropriate cylinder is in its intake stroke.

Misfire with fuel

The exhaust shows clear signs of a 'Misfire with fuel' during the Idle test but also shows signs of it at load speeds. At Idle, the primary cause of the misfire seems to be the reverse blow-by in cylinder e but at higher speeds, it looks like the cause might be a gasket weakness between cylinders 3 (c) and 5 (e).

Possible head gasket weakness in one bank.

The weak exhaust of cylinder 3(c) and weaker exhaust from cylinder 5 (e) can be explained by a head gasket defect (rupture) between the two cylinders such that when one has its power stroke, the other accepts partial combustion products from the cylinder in its intake stroke which also take in fresh air from the manifold. The fact that 5 produces less exhaust than 3 suggests that there might be a bias in the presumed defect.

Unexpected Oscillation in the Exhaust

In both the Idle and Load tests, the exhaust Profiles show a well-defined oscillation throughout the engine 4-stroke cycle. Looking at the first run, we suspected a loose/floppy timing chain/belt. But when we calculate the frequency of the oscillation at idle and load rpm, we see that the wavelength of the oscillation is the same at both speeds, suggesting that the cause might be a reflection in the exhaust system. Real reason is still an open question.

The Engine and test conditions:

A V6 ICE engine was ‘tested’, using the Engine Polygraph technology of Predictive Fleet Technologies, Inc. software in April 2020 using the components of the standard Engine Polygraph kit.

The 2003 engine has 151,195 miles on it with fewer than 5,000 miles per year for the past 10 years. And almost all of those miles were in city traffic of quite short duration. The engine runs well with plenty of power but does have a ‘clicking’ sound at about one per engine cycle (1/2 rpm) and some carbon visible in the exhaust at idle.

Two ‘signatures’ were obtained: one at an idle speed (700 rpm) and the other at a ‘load’ engine speed of about 1400 rpm.

Assessment Methodology:

The Assessment report compares the data from this engine to similar data from many previously assessed engines of a large variety of gasoline and diesel engines. Thus, we call these measures ‘engine integrity’ measures that are used to compare this engine to a generic ICE engine of more than two cylinders. We selected a set of engines as representative and assigned them scores. We then used these as examples for self-learning programs using ‘learn-by-example’ methodology.

All ICE engines with high integrity are presumed to have exhaust patterns that are highly repeatable across all of the cylinders. They should all have a crankcase waveform such that each cylinder in the first rotation has a highly correlated cylinder in the second rotation of the crankcase. (In the case of an engine with an odd number of cylinders, the center cylinder of the firing sequence should be symmetric about the center.) High cylinder correlations (cc near ±1.0) were assigned 1 and very poor correlations were assigned 9 with scores with intermediate values assigned monotonically.

The relative intensity of the 3 other vibrational ranges were all graded as 1 (same as background noise) to 9 being the highest recorded relative intensity. This is for the exhaust vibrational waveform and separately, the crankcase vibrational waveform.

Thus, we end with a Likert-Scale of scores with 1 being 'the best' and 9 being the worst.

Engine level parameters

The 'engine level' scores relate to 3 ranges of the **exhaust** waveform. The main exhaust score reflects the similarity between the **pressure** component of exhaust strokes that are dependent on uniform fuel distribution, good ignition, and good valve & gasket isolation when appropriate for the cylinders: good rings, pistons, PCV valve, and cylinder sleeves. The scores for the **Upper engine** are obtained primarily from the exhaust waveform; **Lower engine** scores are based primarily on the crankcase waveform. Defects in these are serious issues. The higher numerical score is chosen as the larger of the Upper and Lower scores as the Overall engine score.

The low frequency vibrational peaks reflect 'smaller' variations that happen at a higher frequency such as turbulence/vortices in the airflow into and out of the cylinders and manifolds or mismatches on the valve lash adjustment. These affect the Volumetric Efficiency of the engine and are displayed as a volumetric Efficiency score – not the actual volumetric score. Carbon buildup in the manifolds and around the valves are significant causes of these vibrations. A weak valve spring can also cause such vibrations.

High frequency vibrational peaks suggest a 'whistling' that might be caused by carbon 'nuggets' that get lodged between the valve seat and the valve opening. A chip in the valve seat might also cause this.

These low and high vibrational peaks are indicators that the engine is not running as efficiently or as powerful as it should but are probably not leading to a 'broken' engine.

The **crankcase waveform** is likewise represented as scores from the same 3 ranges of the waveform. The basic 'pressure' curve (shown in green) is a sum of the components from all cylinders as the engine goes through its 720° cycle. It is called the **Lower engine** score. This score is a reflection of the 'integrity' of components keeping pressure repeating regularly. The components controlling the crankcase pressure variations are mainly: pistons, piston rings, PCV valve, and gaskets.

The low frequency vibrational peaks in the crankcase reflect variations in pressure due to movement of smaller components, e.g., bearings, rough (corroded or pitted) surface on the cams (the metal of the block and rocker assembly is a good conduit of such vibrations). We label these 'sounds' as rumble and are usually localized to one or a few cylinders.

The high frequency vibrations in the crankcase are likely from metal rubbing on metal with minute roughness of the surface of the metals (not well lubricated). The surface could be rings on cylinder walls. We call this 'scraping'.

Additional engine level parameters are calculated statistics from the cylinder measurements in the exhaust and crankcase, such as median pressure of each cylinder's pressure range, standard deviation of cylinder-specific measures, etc.

Cylinder level parameters

As mentioned earlier, the system calculates a number of features for each cylinder in the crankcase and exhaust: average pressure, pressure range during the cylinder's duration, the cylinder's duration, etc. In addition, in the exhaust we calculate a number of 'pattern' features, and in the crankcase, we calculate the correlation of the curve between all other cylinders to find the best match and store that correlation coefficient as a measure of ‘most like another cylinder in the crankcase’.

The Scoring Models

For each of the six scores (3 for the Upper engine and 3 for the Lower engine), we have developed a mathematical model to take the engine level parameters to provide a set of values that produces a set of scores that represents any ICE of the same ‘integrity’ as previously reviewed by technicians.

Assessment Scores at Idle

Here we show the results of the scoring of the subject engine (3.0L 3100 GM LFW V6) at idle (688 rpm). The signature is identified by the title: 20200402-0001.

Engine Polygraph Assessment

Version Test 6.0

Upper Engine	3	Good upper engine mechanical condition
Volumetric Eff. Score	1	Valve lash very good; no sign of carbon buildup
Valve Seating	1	Valves seated very tight - no sign of carbon causing leakage
Lower Engine	5	Fair lower engine mechanical condition
Rumble	7	Quite a bit of hum or 'rumble' detected in the crankcase
Scrape	4	Some sign of lubrication problems in the crankcase

1	2	3	4	5	6	7	8	9	10

Upper Engine	Upper engine mechanical condition (injectors, valves, head gasket, etc.)
Volumetric Eff. Score	Parts affecting the rate of air exchange through the engine
Valve Seating	Parts affecting tightness of the exhaust valves closure
Lower Engine	Lower engine mechanical condition (pistons, rings, cyl walls, PCV valve, etc.)
Rumble	Hum in the crankcase
Scrape	Screeching in the crankcase indicating poor lubrication

~ 2 ~

Patent No. US 10253716 B2; © Predictive Fleet Technologies, Inc. 2020 All rights reserved
info@EngineAngel.com Phone: 1-833-ENGANGL (364-2645)

Fig. 2. The Assessment Summary for the subject engine at idle.

The Assessment report from EP is shown above and the upper engine looks quite good with little to no carbon buildup. The Lower engine is not so good with ‘quite a bit of ‘hum’. This engine was not even started for the 13 weeks prior to the past 2 weeks; that might explain the moderate lubrication issue.

Model Graphic at Idle

In addition, the Assessment reports displays some graphics to help explain the scores. The first is the signature (simultaneous exhaust and crankcase waveforms) with the engine at idle (688 rpm) shown on the next page. We call this the Model graphic since it represents the mathematical model of the engine cycle.

The upper (exhaust) waveform looks fairly uniform with several short pulses (c and e) and one very high pulse (a) and one high pulse (f). The crankcase shows one huge vacuum while (a) is exhausting. If the crankcase was in good shape, there would be two roughly equivalent vacuums. So the upper and lower scores look reasonable, but maybe a little better (lower value) than the waveforms look.

The exhaust waveform is very green with minor black such that the vibrations do not have meaningful peaks in the lower frequency range so the scores of 1 look right. The crankcase shows considerable vibration with several regions of very black (high frequency) near the vacuum valleys; but more at a less dense lower frequency suggesting quite a bit of vibration at possibly the mm order of magnitude. So the lower engine vibration score seem to make sense.

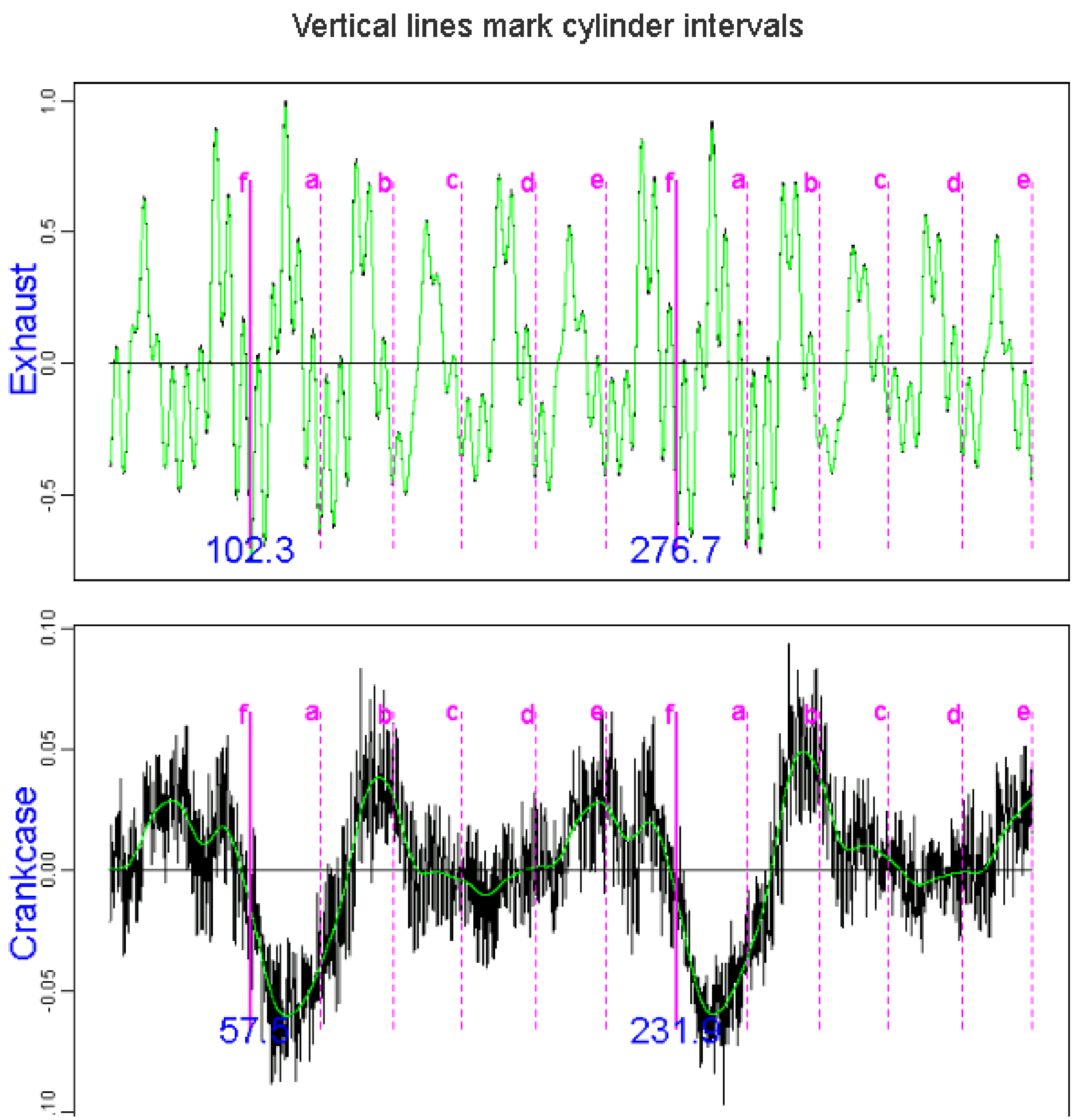


Fig. 3. Signature for 20200402-0001. Engine is a 3.0L 3100 GM LFW V6) at idle. The time markers (ms) define the rpm = 30000 * NumberStrokes / (276.7 – 102.3) = 688 rpm

Two more types of graph are used to gain some more insight on the Assessment report: we call them 'Points' and 'Profiles'.

The Points Graphic at Idle

The Exhaust 'Points' plot represents each cylinder as a colored point at height above the x-axis as the voltage range and distance from the y-axis as the cylinder duration in ms. Using the color chart in the graphic we see that the very high peak is in the (a) cylinder with (f) also high; We also see that (c & e) are at very low voltage (pressure).

The Crankcase 'Points' chart plots the minimum voltage and voltage range in the crankcase for each cylinder. As mentioned above, for engines with even number of cylinders, the cylinders would appear as pairs of very close points near the circle centers in a good engine.

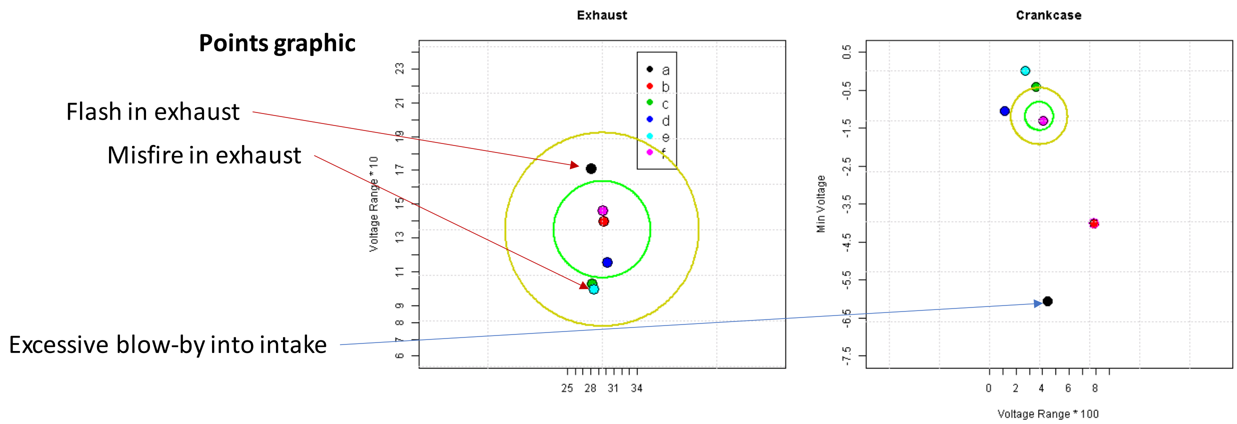


Fig. 4. The Points graphic for the subject engine at idle.

The Profile Graphic at Idle

The Profile graphics show the voltage/pressure from the start of each cylinder duration until its termination for that cycle - from both the exhaust or crankcase waveforms.

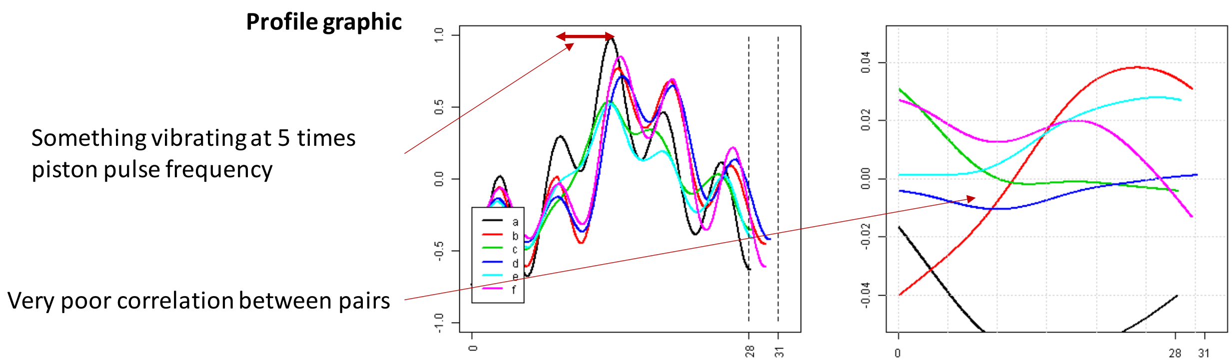


Fig. 5. The Profile graphic for the subject engine at idle.

The exhaust profile graphic shows quite good overlay, cylinder-by-cylinder with durations quite similar. The interesting feature is the 'vibration'/pressure pulsing within the exhaust at 5 times the piston stroke frequency.

The crankcase profile does not show any sign of the pulsing within each cylinder duration. But there is quite poor correlation between the profiles associated with the cylinders. (The color coding is the same for each of the graphics.)

Scoring the Engine at Load

Next, we show the results of the scoring of the subject engine at 'load' (1420 rpm). The signature is identified by the title: 2020-04-02_DC-A2-66-01-50-61_0000001.

Version Test 6.0

Upper Engine	4	Acceptable upper engine mechanical condition
Volumetric Eff. Score	3	Good airflow from intake to exhaust
Valve Seating	1	Valves seated very tight - no sign of carbon causing leakage
Lower Engine	3	Good lower engine mechanical condition
Rumble	6	Very noticeable hum or 'rumble' detected in the crankcase
Scrape	4	Some sign of lubrication problems in the crankcase

1	2	3	4	5	6	7	8	9	10

Upper Engine	Upper engine mechanical condition (injectors, valves, head gasket, etc.)
Volumetric Eff. Score	Parts affecting the rate of air exchange through the engine
Valve Seating	Parts affecting tightness of the exhaust valves closure
Lower Engine	Lower engine mechanical condition (pistons, rings, cyl walls, PCV valve, etc.)
Rumble	Hum in the crankcase
Scrape	Screeching in the crankcase indicating poor lubrication

~ 2 ~

info@EngineAngel.com Phone: 1-833-ENGANGL (364-2645)

Fig. 6x. The Assessment Summary for the subject engine at idle.

Here we see the same engine running at 1420 rpm within minutes of the idle run. This time, the Volumetric Efficiency score is showing more turbulence than at idle. The Lower Engine score has improved significantly for a reason that we will discover with the diagnostic report. The vibrational spectra in the crankcase is quite similar to that see while the engine was idling.

Model Graphic at Load

On this run, the exhaust waveform is again quite 'clean' (little sign of carbon) but the cylinder durations have more variation among the cylinders. Notice that the time between the cycle boundaries is now only 85 ms since the engine is running at 1420 rpm.

The crankcase is much better behaved such that we can visually see the similarities between (a & d), (b & e), and (c & f).

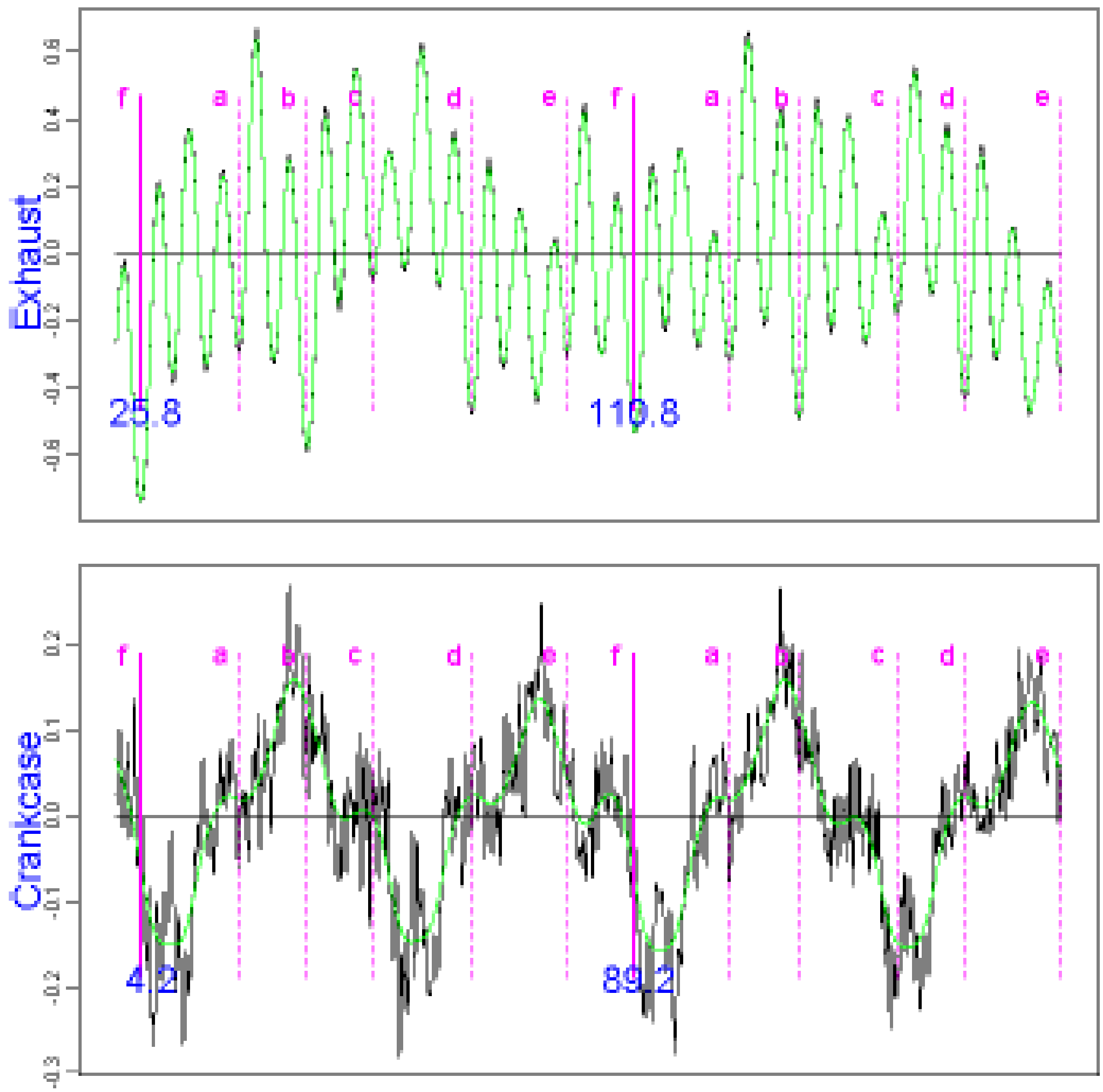


Fig. 7. Signature for 2020-04-02_DC-A2-66-01-50-61_0000001. The engine is running at 1420 rpm.

The Points Graphic at Load

The Exhaust Points graph makes clear that one cylinder (e) has much lower pressure during its exhaust so it is considered to be a misfire. Since the median is between the (a & d), the pink (f) is also low. The deep red (b) is high.

The crankcase shows (a & d) and (b & e) with very good correlation but (c and f) not so well correlated. But a big improvement from the idle run.

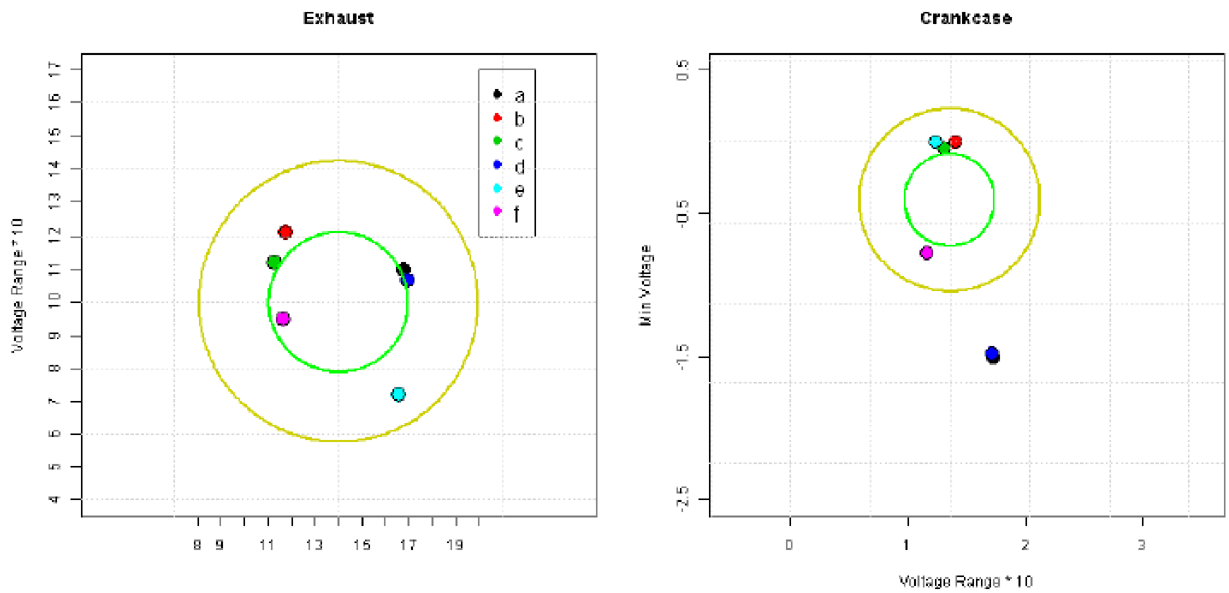


Fig. 8. The Points graphic for the subject engine at load (1420 rpm).

The Profile Graphic at Load

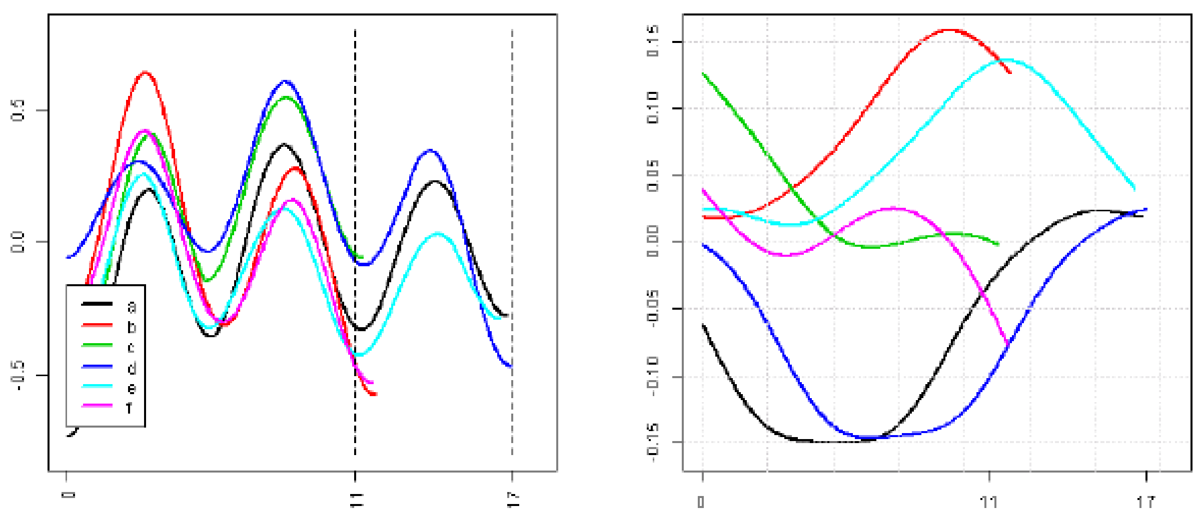


Fig. 9. The Points graphic for the subject engine at load (1420 rpm).

The Profile Graphic from the Load signature shows a significant change from the set at Idle. The exhaust profile shows each cylinder profile with the same shape in two groups of 3. The two groups vary by duration such that one group has two oscillations and the other group has three oscillations.

The crankcase Profile Graphic shows the high correlation between cylinders a & d and b & e; c & f are still not very well correlated. Notice that the correlation allows one curve to be 'slid' to the right or left with no affect – it's the paired shapes that are important.

Diagnostic Methodology

The basic methodology we use for diagnostics is to employ a set of Rules to associate 'Abnormal Observations' in the Engine and Cylinder features with 'Causes' that would produce some or all of the Abnormal Observations. We calculate a 'Confidence' that the cause is present in the engine from the number of Abnormal Observations of the total present that are associated with the listed cause. (An engine often has more than one issue (cause) present. A Cause is not listed unless all of the expected Abnormal Observations are present.

For each Cause considered 'possible', one or more Suggestions are presented to the technician to try to remedy the Cause.

Diagnostics Rules: Abnormal Observations ➡ Suggested Causes ➡ Proposed Remedies

For some 'considered' causes, the sensor data cannot rule in or out if the proposed cause is relevant. In these cases, the Abnormal Observations can have a question. If the answer from your observation is 'no', then reject the proposed cause. If 'yes', the proposed Cause should be considered as more likely.

Rules

A set of rules have been developed for signatures from 'hot' (running) engines and another set for 'cold' (cold-crank) engine signatures. The set of rules will be expanded as we encounter more examples. And these rules have not had much testing yet in the 'real world'. The rule generation process:

1. Identify a problem that is of interest.
2. Identify any restrictions on the type of engine that might be susceptible, e.g., spark/diesel ignition only, not valid for engines with cylinder deactivation, etc.
3. Produce a list of expected abnormal observations if that problem were to exist. If the user might be able to see or smell abnormal conditions (e.g., blue smoke from exhaust, sweet smell from exhaust, etc.) include questions for the user to consider for (in)validating the system conclusions.
4. Map the expected abnormal observations to measurements and calculated features from the EP Analysis.
5. Provide a name for the Cause and a Confidence to indicate what % of the actual observed abnormal observations would be addressed by solution of this cause.
6. Load the text to describe the Abnormal Observations (including questions for the technician), Cause, and Suggestions for the report.
7. Program the rule to trigger the inclusion of the Cause texts and Confidence on the Diagnostic report.
8. Test that the rule does not produce misleading Causes for engines that are known not to have the cause and look for tests of engines that do (or might have) the cause.

Abnormal Observations

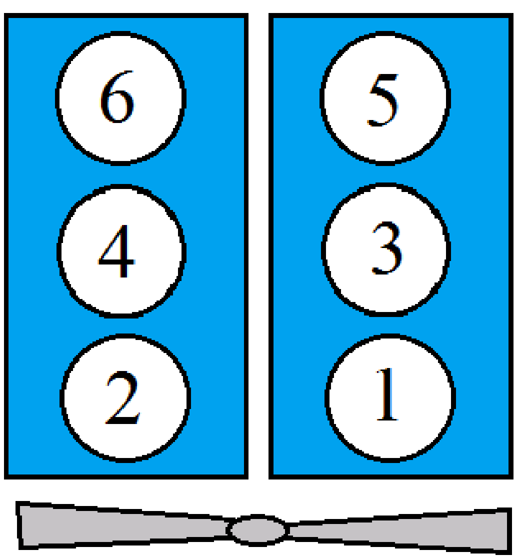
The definition of ‘abnormal’ varies by the type of measurement and the relative ‘distance’ from a ‘normal’ value. All the measurements are ‘normalized’ and ‘distance’ is based on the normalized values. For many measurements, ‘normal’ refers to the median value for all the cylinders, i.e., the value such that the number of values greater than the median is the same as the number below the median. For such measures, normal, high/low, very high/very low, and ultra high/ultra low are names of ‘bins’ that we place the feature values in. For correlations, ±1.0 is considered ‘perfectly’ correlated so only the set of low bins are used to define abnormality.

In this way, all cylinders have all features ‘binned’ as normal or how far abnormal. There are a number of upper and lower engine wide features that are similarly binned for reference in the rules.

Engine Block Layout and Adjacency Matrix

There are a number of ‘conceptually possible’ causes that can be eliminated by referencing the ‘Engine Block Layout and the derived ‘Adjacency Matrix’. We reference the cylinders starting with cylinder 1 and work through the firing order sequence. We use the cylinder numbers as provided by the engine manufacturer to derive the Adjacency Matrix and an associated bank (for those engines with more than one bank of cylinders). Unless we have a method of determining which cylinder we select as cylinder a in our analysis, we chose to assign the cylinder numbers to the letter describing the firing order.

Adjacency and bank identification for each cylinder are important to evaluate rules about gasket failures.



Cylinder Adjacency Matrix

Cylinder	Adj 1	Adj 2	Adj 3	Adj 4
1	3			
2	4			
3	1	5		
4	2	6		
5	3			
6	4			

Fig. 10. Engine Block Diagram and Connectivity table for subject engine.

Cylinder Offset Diagram

The Cylinder Offset Diagram is a way to visualize the simultaneous activity going on in all cylinders as the engine crankshaft rotates through the 720° (4-stroke engine) or 360° (2-stroke engine). The graphic has one row per cylinder and they are stacked in the firing order with nominally cylinder 1 at the top. The other cylinders, as shown in the Engine Block table, placed on lower rows in the firing order as shown in the pink column.

Cylinder Offset Diagram

	Firing Order:		1	2	3	4	5	6						
	crankshaft rotation		0 to 180°			180 to 360			360 to 540			540 to 720		
			60	120	180	240	300	360	420	480	540	600	660	720
a	Fire Seq. 1	Cyl # 1	Power Stroke			Exhaust Stroke			Intake Stroke			Compression Stroke		
b	Fire Seq. 2	Cyl # 2	Comp Stroke		Power Stroke			Exhaust Stroke			Intake Stroke			
c	Fire Seq. 3	Cyl # 3		Compression Stroke			Power Stroke			Exhaust Stroke			Intake Stroke	
d	Fire Seq. 4	Cyl # 4	Intake Stroke			Compression Stroke			Power Stroke			Exhaust Stroke		
e	Fire Seq. 5	Cyl # 5	Exhaust Stroke		Intake Stroke			Compression Stroke			Power Stroke			
f	Fire Seq. 6	Cyl # 6		Exhaust Stroke			Intake Stroke			Compression Stroke			Power Stroke	

	trigger pulse	+1	+2	+3		
Exhaust pulses	#5 exhaust	#6 exhaust	#1 exhaust	#2 exhaust	#3 exhaust	#4 exhaust
Crankcase pulses	#1 crankcase	#2 crankcase	#3 crankcase	#4 crankcase	#5 crankcase	#6 crankcase
intake vacuum pulses	#4 intake	#5 intake	#6 intake	#1 intake	#2 intake	#3 intake

Fig. 11. Cylinder Offset Diagram for the subject engine.

It is tempting to count cylinder boundaries but that is misleading unless one is working with a 4-cylinder engine. For a 6-cylinder engine, the duration of a single stroke is 1.5 times the duration of a 'cylinder boundary'.

As the crankshaft rotates, the status of each cylinder – its stroke and how far into the stroke it is, is clear for all cylinders, simultaneously. This can be valuable in diagnosis.

The Diagnostics

We will go through the diagnostics for our subject engine in a conversational way, looking at the graphics. The program looks at each rule, one at a time, focused on the abnormal observations. So most rules fail by not finding all the abnormal observations present for most rules.

Diagnostics at Idle

When we look at the idle graphics, cylinders c & e look pretty weak in the Model graph, exhaust waveform. The idle exhaust Points graph doesn't look too bad since all points are in the yellow circle and quite close to the green circle; but we do see the cylinders c & e at the bottom and we see a at a very high level (fuel flash in the exhaust?, or injector pintle too large?). This condition we call 'misfire with fuel'. But why the misfire?

We see a very big vacuum in the Model graph, crankcase waveform. A primary way that crankcase vacuums get very large is when a piston has compression rings that allow the intake of a cylinder to suck crankcase vapors into the cylinder. This can cause the cylinder to have too little oxygen for good combustion. And a cylinder with misfire will have relatively little exhaust pressure and throw unburnt fuel into the exhaust system where it might flash in the catalytic convertor.

So what cylinder is intaking while cylinder a is exhausting? We look at the Cylinder Offset Diagram and see that a is exhausting from 180° to 360° while e starts intaking at 120° to 300°, a 120° overlap. f also overlaps its intake for 120° with a's exhaust – but f has a good exhaust.

So we conclude that the compression rings of cylinder e are allowing reverse blow-by into its cylinder so its next power stroke will be weak and hence not much exhaust pressure. Likely there is carbon 'packing' around the compression rings preventing the normal flexing as the piston goes up and down the cylinder walls. This might cause some of the vibrations 'heard' in the crankcase.

But why is c's exhaust weak?

> It could be that c has a leak around one of its intake valves so that during compression and power strokes there is a drain of pressure so by the time it exhausts, there is not much more to go out the exhaust.
>
> Alternatively, we see on the Adjacency chart that c & e are adjacent in the same bank. This suggests the possibility that when e has its poor burn during its power stroke, it overlaps the first third of c's intake stroke and so can inhale some of e's combustion product with very low O_2.

The third abnormal observation is the very regular 'oscillation' showing in the exhaust pressure curves of the Profile graphic for each cylinder. As indicated on the graphic as the red line with arrows on each end, it can be seen that the arrow length is 1/5 the duration of the average cylinder duration. The frequency of the 4-stroke cycle is 1/(0.1744 ms)= 5.73 Hz at this idle speed. So the piston stroke frequency is 6 times that = 34.40 Hz and 5 times that is 172 Hz for the frequency of the oscillation. This could be a result of a harmonic in the exhaust manifold, a floppy timing chain/belt, etc. Physical inspection might be needed to identify the cause.

Diagnostics at Load

Next, we look at the same engine running at ‘Load’ with an rpm of 1420. We remember the significant improvement in the score for the crankcase pressure. This is quite unusual – what happened to the very big vacuum while e is intaking? Now a & d are very well correlated in the Points, Profile, and Model graphics.

One possibility is that when the engine was running at ½ the speed, the intake stroke took twice as long and so was able to obtain twice as much crankcase vapor as when the engine is running at the higher speed.

Another possibility is that the compression rings ‘broke loose’ from the carbon packing at the higher speed. So we ran another idle test and it ‘duplicated’ the results we show here. So we reject this hypothesis.

We still see the misfire in e, and a weak misfire in c. In addition, b looks extra strong so we still have a misfire with fuel, but it is on the border line. A possible reason that e misfires with fuel is that the gasket weakness suspected from e to c allows flow of partial combustion products (without very much O_2 through the gasket rupture for ½ the time as during the idle operation) from c to e, affecting the power and exhaust from e in this cycle and c in the next cycle.

What about the oscillations in the exhaust? In the exhaust Profile graphic, we see that 3 cylinders have 3 pulses and 3 cylinders have 2 pulses for an average of 2.5 oscillations per cylinder. Repeating the calculation from the idle signature, we get a frequency of the 4-stroke cycle is 1/(0.085 ms)= 11.8 Hz at this load speed. Hence the cylinder stroke frequency is 6 * 11.8 Hz = 70.6 Hz and the strange oscillation is at 176 Hz, very close to the 172 Hz that we obtain from the idle signature. We conclude that this oscillation is independent of the engine speed and so must relate to some geometric factor of the manifold or muffler system.

Future Work

We have the structure in place to analyze engines ‘running’ in ‘Idle’, ‘Load’, and ‘Cold-crank’ conditions.

The set of rules we employ will increase as we experience more engines with varied issues.

The applications EP web and EPReader are enabled for multiple languages, but the texts and screens are not translated until there is a customer need.

The content is largely translated into Spanish.

We are working on a wireless interface to the engine’s ECM to pick up a more accurate rpm estimate and other engine data so that an input rpm estimate would not be needed.