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DEVELOPING A KNOWLEDGE BASE FOR DETECTION OF POWERTRAIN FAILURES BY REVERSIBLY SEEDING ENGINE FAULTS

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ABSTRACT

Engine performance is traditionally measured in a dynamometer where engine speed, torque, and fuel consumption measurements can be made very accurately and environmental conditions are well controlled. Durability testing is also carried out in a dynamometer to assess reduction in engine output due to normal aging. However, the symptoms associated with incipient failures are not often studied since it requires either stressing engine components above their recommended limit or exchanging parts of known deviation with normal ones. This work describes a methodology for seeding faults in an engine by electronic means so that they can be reversibly turned on and off in a controlled fashion. The focus is on seeding faults that produce changes in engine output so that comparison between precise measurements done with laboratory instruments may be compared with estimates derived from on-board measurements. Thus, we have relied on a rather broad spectrum of measurement capabilities implemented in the dynamometer in order to acquire comprehensive information on the normal and abnormal behavior of the engine. A variety of engine parameters from the PCM, from add-on sensors and other instrumentation can be recorded and analyzed to detect statistically significant changes induced by the seeded faults. Thus, it is possible to build a knowledge base of measurable symptoms of abnormal behavior and study whether they could also be detected with practical on-board devices for implementing Condition Based Maintenance of powertrain systems.

INTRODUCTION

Implementing Condition Based Maintenance (CBM) to service vehicles more efficiently relies on being able to infer actual Wear & Tear by combining information of the observed usage and field operating conditions of the asset with known durability data and previous service records. However, detecting incipient failures due to unpredicted deterioration requires developing schemes for monitoring anomalous performance of the asset while it is in use. Gathering knowledge of symptoms related to abnormal behavior from field observations is laborious and often impractical because parts will fail at unpredictable times, the level of performance deterioration cannot be easily measured and noise factors that can obfuscate the faults cannot be readily quantified. One approach for developing a knowledge base regarding the behavior of both healthy and degraded systems focuses first on comprehensive testing of subsystems in a controlled environment rather than at the vehicle level in the field. The sensitivity and robustness of newly proposed detection methods can be first assessed with experiments under controlled conditions, when perturbations of increasing magnitude can be induced. Validation of promising monitoring schemes will be then continued in the field.

One readily available method for studying engine performance is to operate it in a dynamometer environment where accurate measurements of the inputs to the engine, such as the air-mass and fuel, and of its output, in terms of torque, speed and heat losses, can be accurately performed. Our investigation has focused on creating faulty operating conditions in an engine by perturbing the output of its electronic components. This paper describes the procedures for inducing abnormal engine behavior by altering the transfer function of either pressure sensors (gain and/or bias) or the resistance of temperature sensors that are part of the control systems. We discuss the changes we have been able to induce in either fueling or air induction by means of skewing either the Injection Control Pressure or the Boost Pressure sensor, respectively, and the corresponding deviation observed in engine output (torque).

Our proposed method for simulating engine faults has the advantage of being able to turn the perturbation on/off in a predictable, reversible and repeatable way so that comparison between normal and abnormal behavior can be carried out efficiently. More important, these perturbations can be induced at different levels simulating an incipient fault and step-wise engine performance changes can be induced. A fairly complete picture of the engine response is acquired by recording not only engine parameters readily accessible with traditional on-board methods, such as recording messages broadcast on the CAN communication bus (J1939) or parameters (PIDs) readable with a Scan Tool, but also by means of additional high accuracy laboratory instrumentation and other types of sensors installed on the engine which are not readily deployable in the field. The unique range of instrumentation on which we have relied for this project makes it possible to conduct an in-depth evaluation of whether the quality and quantity of information readily available from the PCM is adequate for developing on-board monitors that detect engine performance loss. Moreover, the variety of sensing capabilities embedded in the experimental set-up provides us with a rich domain of information with which to explore the potential benefit derived from alternative on-board sensing schemes.

EXPERIMENTAL SET-UP

Fig. 1 is a schematic representation of the major building blocks of the experimental set-up used in this project. It highlights control equipment, sensors on the engine (production and add-on), laboratory instruments, the fault seeding apparatus, and the two data acquisition systems (DAQ).

Engine

Our investigation was based on the military version of a production engine mounted on an Eddy current dynamometer at the dynamometer facility of the Mobility Group at the Detroit Arsenal. The engine was an in-line 7.2L 6 cylinder diesel engine with a wastegated turbocharger, positioned at the mid-point of the exhaust manifold, and Hydraulic activated /Electronically controlled Unit Injectors (HEUI) with no EGR and no exhaust aftertreatment. The alternator was disconnected and power was supplied by a 24 V battery pack that was continuously trickled-charged while the engine was running.

The air charge was cooled with a high efficiency water cooled heat exchanger positioned on the side of the engine.

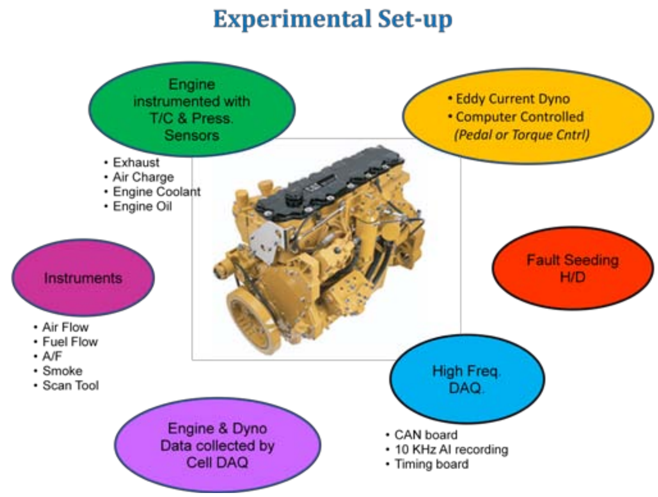

Figure 1. Schematic view of the instrumentation used in the experiments.

The air temperature was controlled at the desired set-point by regulating the inlet water flow in the heat exchanger. The temperature of the cooling water was not regulated. The typical set-point for the air charge temperature was 127 degF, as used in other durability tests carried out in these facilities. The engine coolant temperature was also externally controlled and the temperature set-point was 205 degF. Different set-point values could also be selected.

Instrumentation

The engine was instrumented with a series of thermocouples and laboratory grade pressure sensors that monitor fluid temperatures and pressures (Engine Coolant, Air Charge, Exhaust, Engine Oil, Fuel) at several locations in the engine and in the external cooling systems. The exhaust gas temperature was measured at each exhaust port as an indication of mean combustion differences between cylinders. Pressure and temperature were also measured at the two inlet ports of the turbocharger, corresponding to the left half and right haft of the exhaust manifold, and downstream of the turbo in the exhaust duct. Additionally, the temperature and pressure of the air intake, before and after the air charge cooling system and before and after the turbo, were measured so that the air handling system could be closely monitored. Pressure sensors were also added in the engine cooling system. In addition to this large number of monitoring devices, other temperature and pressure sensors were used to monitor whether the dynamometer was operating within the desired range.

The engine speed and torque values were obtained from the dynamometer controller instrumentation. The engine output was regulated by the dyno controller by means of an electromechanical device that actuates the engine pedal. The dynamometer was operated in two modes: in one case the Pedal Position was set while the engine speed was kept at a desired set-point by means of the dyno brake ("open loop case", used to measure the engine output for a given driver demand, for instance, 100% pedal); in the other case ("closed loop") engine speed and torque were maintained at the requested set-point by means of the dyno brake and by changing the pedal position with the servomechanism.

<table>
<tr><th>Param</th><th>Units</th><th>Param</th><th>Units</th></tr>
<tr><td>SPEED</td><td>RPM</td><td>EXH B4 TURB1</td><td>DEG F</td></tr>
<tr><td>TORQUE</td><td>LBS/FT</td><td>EXH B4 TURB2</td><td>DEG F</td></tr>
<tr><td>BHP</td><td>HP</td><td>EXH STACK</td><td>DEG F</td></tr>
<tr><td>pBARO</td><td>Hg</td><td>AIR DELTA P</td><td>H2O</td></tr>
<tr><td>BFSC</td><td>LBS/HP/HR</td><td>AIR AFT</td><td>COMP|PSIG</td></tr>
<tr><td>POSIT</td><td>%</td><td>AIR AFT CAC</td><td>PSIG</td></tr>
<tr><td>FUEL</td><td>LBS/HR</td><td>AIR RSTR</td><td>H2O</td></tr>
<tr><td>WATER CAC</td><td>GPM</td><td>CRANKCASE</td><td>H2O</td></tr>
<tr><td>WATER TOWER</td><td>GPM</td><td>FUEL B4 FIL</td><td>PSIG</td></tr>
<tr><td>CRANKCASE</td><td>ACFM</td><td>OIL GALLERY</td><td>PSIG</td></tr>
<tr><td>AIR AMBIENT</td><td>DEG F</td><td>FUEL AFT FI</td><td>PSIG</td></tr>
<tr><td>AIR B4 FILT</td><td>DEG F</td><td>FUEL SUPPLY</td><td>PSIG</td></tr>
<tr><td>AIR AFT FIL</td><td>DEG F</td><td>FUEL RETURN</td><td>PSIG</td></tr>
<tr><td>AIR AFT</td><td>COMP|DEG F</td><td>CLNT B4 ENG</td><td>PSIG</td></tr>
<tr><td>AIR INTAKE</td><td>MANIF|DEG F</td><td>CLNT AFT EN</td><td>PSIG</td></tr>
<tr><td>OIL SUMP</td><td>DEG F</td><td>CLNT CAP</td><td>PSIG</td></tr>
<tr><td>OIL GALLERY</td><td>DEG F</td><td>EXH B4 TURB</td><td>PSIG</td></tr>
<tr><td>FUEL SUPPLY</td><td>DEG F</td><td>EXH B4 TURB</td><td>PSIG</td></tr>
<tr><td>FUEL RETURN</td><td>DEG F</td><td>EXH STACK</td><td>H2O</td></tr>
<tr><td>FUEL B4 HTR</td><td>DEG F</td><td>SMOKE METER</td><td>FSN</td></tr>
<tr><td>FUEL AFT HT</td><td>DEG F</td><td>AIR AFT</td><td>FILT|H2O</td></tr>
<tr><td>FUEL BEAKER</td><td>DEG F</td><td>AIR FLOW</td><td>MTR IN|H2O</td></tr>
<tr><td>CLNT B4 ENG</td><td>DEG F</td><td>AIR FLOW</td><td>MTR OUT|H2O</td></tr>
<tr><td>CLNT AFT EN</td><td>DEG F</td><td>AIR COMP</td><td>IN| H2O</td></tr>
<tr><td>WATER CAC I</td><td>DEG F</td><td>DYNO H2O</td><td>IN DEG F</td></tr>
<tr><td>WATER CAC O</td><td>DEG F</td><td>DYNO H2O</td><td>OUT DEG</td></tr>
<tr><td>WATER TWR IN</td><td>DEG F</td><td>WATER FU</td><td>HTR IN P</td></tr>
<tr><td>WATER TWR OU</td><td>DEG F</td><td>WATER FU</td><td>HTR IN D</td></tr>
<tr><td>EXH PORT 1</td><td>DEG F</td><td>STEAM FU</td><td>HTR IN D</td></tr>
<tr><td>EXH PORT 2</td><td>DEG F</td><td>DYNO OIL</td><td>PSIG</td></tr>
<tr><td>EXH PORT 3</td><td>DEG F</td><td>TRANSDUCER</td><td>RACK DEG F</td></tr>
<tr><td>EXH PORT 4</td><td>DEG F</td><td>DYNO H2O</td><td>PSIG</td></tr>
<tr><td>EXH PORT 5</td><td>DEG F</td><td>WATER TW</td><td>PSIG</td></tr>
<tr><td>EXH PORT 6</td><td>DEG F</td><td></td><td></td></tr>
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Table1. List of engine parameters measured by external sensors and instruments which are recorded by the dyno data acquisition.

While Eddy current dynos are typically used for testing engine performance and durability, this dynamometer cell was purposely equipped with a number of other high precision instruments to measure the inputs to the engine (air and fuel) and its output (torque, heat and crankshaft dynamics) especially suitable for studying engine performance changes due to subsystems perturbations. The intake air flow was measured with both a Laminar Flow device and a Vortex Shedding meter. The fuel consumption was measured by a differential Coriolis system with a response time on the order of 1s. The exhaust air-to-fuel ratio was obtained with a Lambda meter. Soot could be sampled at steady state with a Smoke meter. Since these instruments, except the smoke meter, have relatively fast response times (1s or better), data could be acquired during transition between two operating points and assess how quickly the engine output stabilized after the transient. Since the fault seeding experiments require repeating a given test sequence several times, it is important to understand how quickly the engine output stabilizes after a transient and/or perturbation for expediting the experiments.

Since the engine speed and torque measured by the dynamometer instrumentation were filtered, other instruments with a higher frequency response have been added to measure engine speed and torque fluctuations and evaluate combustion maldistribution between cylinders. A broad band torque sensor (strain-gage type) was mounted in-line between the engine and the dyno coupler to measure torque fluctuations due to combustion events and torque instabilities during transitions. Moreover, a high resolution laboratory encoder was mounted in front of the engine dampener for measuring crankshaft rotational speed accurately since speed fluctuations can be correlated with torque fluctuations. Additionally, a Hall-type sensor was mounted on the flywheel housing facing the ring-gear as another encoder at the back of the engine for investigating the effects of crankshaft torsional oscillations.

The pressure sensors with which the engine was instrumented are meant for mean value measurements. Thus, we have relied on a new type of low-cost piezoelectric device, potentially suitable for on-board application, to investigate the benefit of measuring pulsation variability in the intake and exhaust system related to uneven combustion events. These pressure fluctuations should parallel those observed in torque and crankshaft acceleration. The device is commercially available and detects pressure fluctuations (ac component of pressure) in either exhaust flow or in a low pressure fuel line by contacting the fluid through a small orifice. It is typically used as a low-cost, easy to install diagnostic tool for identifying ignition and fuel system problems in a vehicle during repair in the shop. Three of these sensors were employed for this project, one mounted in the intake system (after the CAC), one in the exhaust (stack), and one attached to the oil dip-stick tube to detect blow-by.

Fault Seeding

Fault seeding was accomplished by custom built circuits. A Break-out Box (BoB) was used to tap into the harness that connects the PCM to the engine sensors (timing, temperature and pressure) and actuators (injectors and PWM valves for controlling Boost and Injection Control pressure). The signal output and common of the sensors measuring Fuel Injection and Boost pressures were broken here and redirected to a custom designed analog device that modifies ("skews") the voltage signal output to simulate a change in the device gain (the gain multiplier ranges from 0.5 to 1.5) and/or bias (range from -1V to 1 V). The skewed output was then connected to the PCM harness at the BoB. Only one sensor at a time was perturbed in these experiments. Similarly, the resistance of the thermistors used to sense the Engine

Coolant and the Intake Air Charge temperatures was increased/decreased by a variable resistor network, inserted in the high signal line either in series or in parallel through the BoB, so that the PCM would sense a lower/higher temperature, respectively, than the true temperature by a selectable amount. The perturbation to either the pressure or temperature sensor could be remotely turned on and off from the dyno control room by means of relays embedded in the circuitry for ease of monitoring the effect of a perturbation.

Combustion instability was induced by interrupting fuel injection to one of the six cylinders at the time. This was achieved by either opening the line carrying the solenoid actuation current at the BoB or by means of the programmed functionality available in the OEM Scan Tool used for assisting the technician to perform repairs. To avoid prolonged stress on the dyno joint, the second method was preferred since the perturbation could be introduced for short periods of time.

To study potential engine output loss caused by added impedance in the intake air flow (that is, simulating a plugged air filter), a butterfly valve was placed downstream of the two air flow measuring instruments, approximately six feet upstream of the air inlet to the turbocharger. The valve closure could be changed in nine steps ranging from completely open to fully closed. Another butterfly valve was placed at the end of the exhaust pipe before the vent, roughly 20 feet from the turbo outlet. This valve was actuated by a stepping motor so that fine rotational settings of the valve (about 2 degrees) could be repeatably selected.

Some of the experiments were carried out with DF2 fuel, and subsequently repeated with JP8 that has lower energy content.

Data acquisition

The dynamometer cell DAQ was designed for filtering and recording at low rate the analog output of a very large number of parameters related to the operating conditions of the engine, dynamometer and cell environment. As shown in Table 1, the list includes signals from the laboratory instruments, from the thermocouples and pressure sensors with which the engine was instrumented, from the five production engine sensors to be perturbed, from the dynamometer controller and from other devices monitoring the cell operating conditions. Because of the large number of channels, the maximum achievable rate was about 0.7Hz. This dataset is referred to as the Dyno data in this paper.

To acquire signals with higher frequency content, we relied on a FPGA-based system that included a CAN board, a 16 bit Analog board, and a Timing board with 100 ns resolution. The system was driven through a real time communication interface, custom developed to meet the requirements of this project, running on a host computer to which the data was continuously streamed for recording via Ethernet. This system is comparable to high-end types of vehicle data recorders that could be retrofitted to a vehicle for implementing a health monitor.

Messages broadcast on the engine communication bus (J1939 protocol at 250 KBauds) were continuously recorded so that engine data derived from the PCM could be compared to measurements done with the laboratory instruments. The engine operating parameters (CAN data) available on the bus for this engine configuration are listed in Table 2 with their rate and resolution. The table also shows whether the same parameter was measured independently with another device and recorded by the Cell DAQ. Notice that there is no independent measurement of the oil high pressure line which pressurizes the fuel in each injector.

Signals from analog sensors, containing high frequency information related to combustion events, were recorded at 10 KHz by means of the Analog board. They included: the fast response torque sensor, the three ac pressure sensors, the primary (CAM1) and secondary (CAM2) variable reluctance sensors used by the PCM to adjust injection timing (there is no crankshaft sensor in this engine), an inductive current meter inserted in the Cylinder 1 actuation line at the BoB to monitor injection timing, and in some other instances, the injector driver signal for another cylinder. High frequency recording was enabled for short windows of time (snapshots) ranging from 1 to 30 s, selectable by the user according to the specific conditions of the test. The snapshot was triggered manually by the operator from the DAQ interface and plots of the recorded data were displayed at the end of the snapshot.

The Timing board was used to record with 100 ns

CAN Param	Units	Rate (ms)	Res.	Cell Param	Units
EngSpd	RPM	15	0.125	EngSpd	RPM
Load	%		1	Load	Lb*Ft
BoostPres	KPa	500	2	AirB4Mani	psi
InjCtrlPres	MPa	500	0.004	n.a.	
ManiIntAitT	degC	500	1	AirIntMani	degF
EngCoolT	degC	1000	1	CoolAftEng	degF
OilPres	KPa	500	4	OilGallery	psa
ElPot	V	1000	0.125	n.a.	
CmdFuel	L/hr	100		FuelFlow	PPH
Pedal	%	50	0.25	Throttle	%
LoadAtSpd	%	50	0.125	n.a.	
NomFric	%	250	100%	n.a.	
DesEngSpd	RPM	250	0.125	n.a.	

Table 2. Engine operating parameters available on the communication bus and equivalent measurements reported by the dyno data acquisition.

resolution the timestamps of pulse edges derived from 5 devices monitoring the crankshaft rotation. These were: a laboratory-grade encoder, whose output was set at 36 pulses per revolution; the encoder index marking each revolution; the TTL signal from the Hall-type sensor mounted facing the ring-gear; the primary and the secondary CAM sensors after their voltage output is transformed into TTL signals by a custom-built Trigger Schmitt-type circuitry. This recording was started by the same manual trigger used for the analog recording and lasted the same length of time.

Since the analog signals are recorded at constant rate while the CAN messages and the timing data are event-based signals that are asynchronous, the data are saved in three different files that are precisely time aligned by the system internal clock. Time alignment with the low-rate data recorded by the Cell DAQ is done on post-processing on the basis of engine speed signatures.

RESULTS and DISCUSSION

Most of the experiments discussed in this paper have been conducted stepping the engine through nine speed/torque points, representative of field conditions, and holding the engine at each step for a short period of time (typically 40 to 90 s). Table 3 shows the operating points for a typical test sequence during which the dynamometer controls the engine speed and torque. At each engine speed the torque is stepped up through three values representing the mid/high torque range (this engine has a max output rating of 800 Lb*Ft at 1450 RPM with JP8 fuel and a recommended top engine speed of 2400 RPM). Three optional low torque points completed the sequence which could be skipped in selected tests.

This test sequence was repeated many times, with and without a seeded fault, since replications were needed to establish repeatability of operating conditions and measurements. Additionally, these repeated measurements are necessary for developing machine learning models, such as those based on Neural Networks.

ID	EngSpd	Torque
(#)	(RPM)	(Lb*Ft)
Stab	1450	700
P11	1450	400
P12	1450	550
P13	1450	700
P21	1800	400
P22	1800	550
P23	1800	700
P31	2200	400
P32	2200	550
P33	2200	700
P41	1450	300
P42	1800	300
P43	2200	300
Idle	700	35

Table 3. Engine operating set-points for the test sequence in speed/torque control mode.

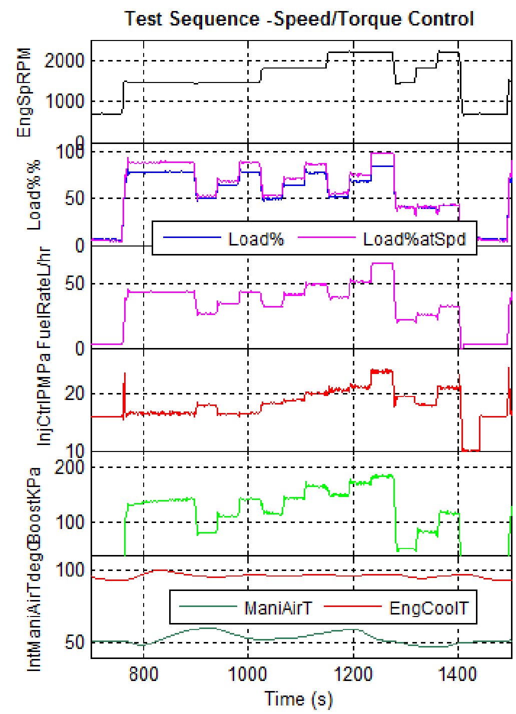

Figure 2. Engine operating parameter timeseries acquired from the CAN communication bus.

In other instances, the test profile was repeated with the dynamometer controlling engine speed but not torque. In that case, the Pedal Position is set at the mean value observed during the test in speed/control mode. Other tests were carried out at 100% throttle (Performance Test) to measure the maximum engine output and check that the engine performance had not changed over time. Fig. 2 shows plots of engine parameters acquired from the CAN communication bus as a function of time during the basic test sequence with no seeded faults. Notice that an idle step was followed by a stabilization step at low speed and high torque (1450 RPM/ 700 Lb*FT) so that the coolant and air charge temperature could settle within the desired range. During the steady-state steps, the engine coolant remained within +/- 3 deg F of the set-point (205 degF), while the air charge temperature was slow to stabilize around 127 degF and was seen to drift within a 25 degF band because the CAC control parameters were optimized for the high torque range. Since in these tests the torque changes from 300 to

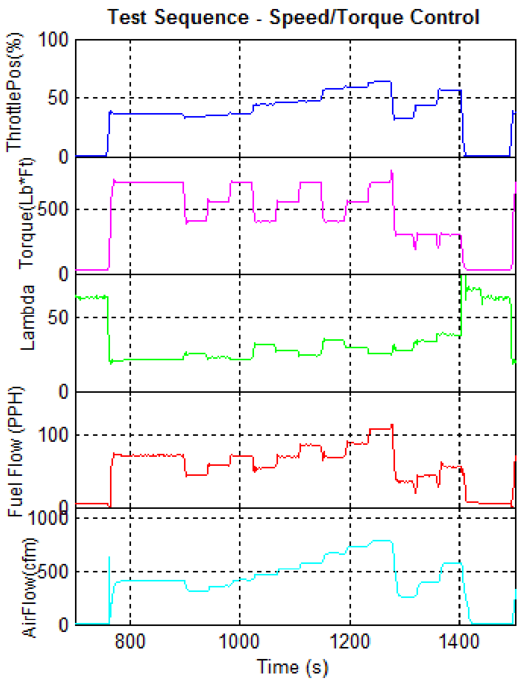

Figure 3. Timeseries of engine operating parameters from laboratory instrumentation and recorded with the Cell DAQ.

700 Lb*Ft, we have not attempted to achieve tight temperature stabilization, as done when measuring rated engine output or BSFC, since the test would become too long. However, we have optimized the test sequence to avoid large air charge temperature excursions, especially toward higher temperatures, since the PCM gradually decreases the amount of injected fuel when the air charge temperature rises above 160 degF to protect the turbocharger against elevated exhaust temperature.

The CAN data in Fig. 2 are compared with equivalent data acquired through the cell instrumentation. Fig. 3 shows timeseries of the Intake Air Flow, Fuel Flow, Air-to-Fuel ratio, Torque and Pedal Position (Throttle%) recorded by the cell DAQ at low rate. A more detailed picture of the engine operating condition is gained from analyzing additional parameters recorded through the cell DAQ. For instance, the plots in Fig. 4 illustrate differences in temperature between the exhaust ports and downstream the turbocharger (Stack) while Fig. 5 shows the exhaust pressure upstream and downstream of the turbocharger together with the intake pressure.

These plots are useful to assess engine stabilization although slow drifts in temperature are caused by the exhaust system walls equilibrating in temperature. The exhaust temperature is an important parameter since it affects the pressure on the turbocharger, thus, the induction process. Also, the turbocharger needs to be protected from overtemperature. Notice that the temperature traces show a faint drift after the first rapid change due to the torque transition between steps. The pressure, however, appears to stabilize more quickly than temperature as indicated by the plots in Fig. 5

The plots in Fig. 4 indicate that exhaust temperature in the port increases as a function of torque (more heat is generated because more fuel is burnt) but decreases as a function of increasing engine speed (higher flow and A/F). When either the fuel system or the induction system malfunctions, the temperature signature could be used as another diagnostic. Unfortunately, there is no exhaust temperature sensor in this application as it would be found in a platform with

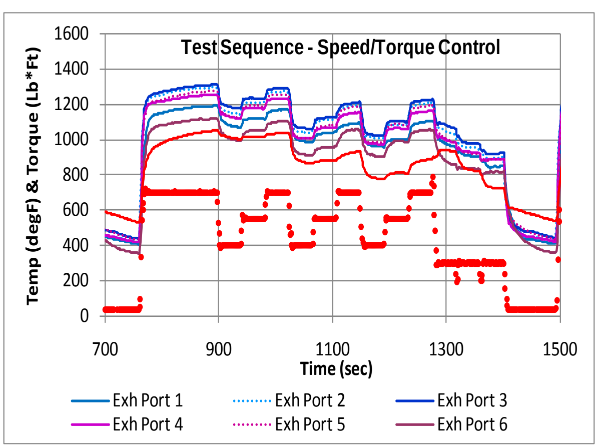

Figure 4. Traces of the exhaust temperature at different locations.

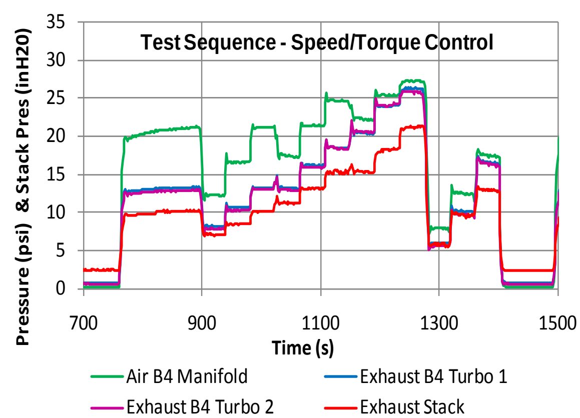

Figure 5. Traces of pressure signals in the intake and exhaust system.

EngSpd	Torque	Fuel Flow	AirFlow	A/F	Tturb1	Tturb2	Pturb1	Pturb2	AirB4M	CoolT	AirIntT
1450	0.8%	0.6%	1.2%	1.6%	0.9%	1.0%	1.0%	1.2%	0.6%	0.1%	2.2%
1600	0.6%	0.5%	0.8%	1.0%	0.3%	0.3%	0.6%	0.6%	0.2%	0.0%	1.3%
1800	0.4%	0.4%	0.8%	1.1%	0.4%	0.3%	0.9%	0.5%	0.2%	0.1%	1.3%
2000	0.3%	0.9%	0.7%	1.0%	0.4%	0.2%	1.0%	0.7%	0.3%	0.1%	0.7%
2200	0.4%	0.7%	0.7%	1.0%	0.4%	0.2%	0.9%	0.5%	0.1%	0.1%	0.6%
2400	0.7%	1.1%	0.7%	1.1%	0.7%	0.6%	0.9%	0.5%	0.1%	0.0%	0.5%

Table 4. The table reports the variability of engine parameters recorded by the Cell daq at different engine speed during eight Performance tests (100% throttle) carried out on different days. The variability is given as the ratio of the mean standard deviation over the mean value of the measurements over 20 s.

aftertreatment. However, one of the goals of this project is to evaluate other sensing methods that provide information on abnormalities in the engine performance.

Temperature differences between exhaust ports may be partly due to geometric effect but they may also reflect combustion differences between cylinders. A small pressure difference (less than 0.5 psi) was observed between the two inlet ports to the turbo under some operating conditions consistent with the observed difference in temperature.

These temperature and pressure features will be addressed in conjunction with the analysis of the high frequency torque data and of the crankshaft speed fluctuations which are related to cylinder-to-cylinder combustion differences. A seeded fault may also amplify differences between cylinders and induce instabilities.

We stress that, when evaluating parameter features that can be used as fault indicators, it is imperative to discriminate between test-to-test variations caused by noise and/or by system variability and the actual changes induced by the perturbation. Therefore, we need to establish first the detection limit for specific measurements. Specifically, we must establish the measurement repeatability and the stability of the engine over the time during which the experiments were conducted in order to prove correlation between features extracted from the data and the seeding of a fault.

EngSpd	Load%	CmdFuel	Boost	InjCtlP	EngCoolT	ManAirT
1450	0.6%	0.2%	0.8%	1.0%	0.3%	0.3%
1600	0.4%	0.2%	0.8%	1.1%	0.4%	0.3%
1800	0.3%	0.3%	0.7%	1.0%	0.4%	0.2%
2000	0.4%	0.1%	0.7%	1.0%	0.4%	0.2%
2200	0.7%	0.1%	0.7%	1.1%	0.7%	0.6%
2400	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 5. Variability of CAN parameters calculated for the same Performance tests used in the data of Table 4.

Table 4 gives the variability observed over eight Performance tests carried out on eight separate days for eleven engine parameters related to engine output. The measurements were done with the external sensors and instruments and recorded by the Cell DAQ. The variability, given in percentage, is calculated as the ratio of the standard deviation over the mean of measurements done over the last 20 s of each steady state step in the Performance Test (test carried out at 100% pedal).

Similarly, Table 5 shows the variability for some of the CAN data calculated for the same tests. The data shows that the variability of most parameters is better than 1 percent. Similar values are obtained for other types of tests such as the one at mid/high torque described in Table 1.

Because our experiments relate to altering the engine sensor calibration in order to perturb engine operating conditions, it is important that we establish correlation between values of engine operating parameters derived by the PCM with the actual values measured with the external instrumentation.

Table 2 shows parameters measured both by engine sensors and by external devices. Fig. 6 shows plots as a function of time of the ratio of the PCM indicated value (CAN data) over the value of the corresponding external measurement (Dyno data).

The ratio for Boost Pressure is found to be 1 +/- 0.02 over the test speed/torque range excluding transients and the idle portion when the pressure is essentially zero. The ratio for

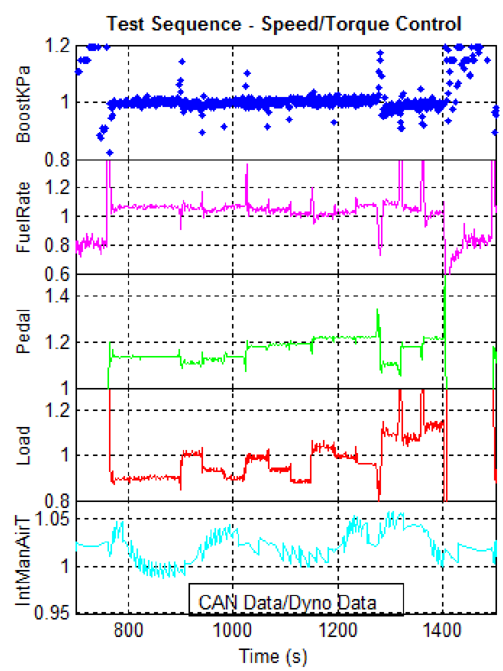

Figure 6. Plots of the ratios of CAN data and Dyno equivalent data after normalizing for differences in units.

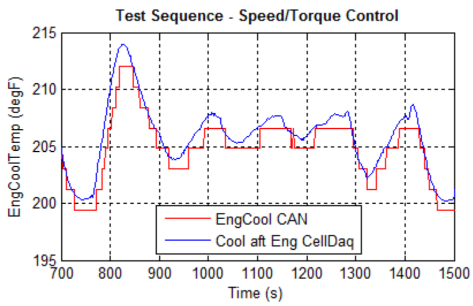

Figure 7. Plot of the Engine Coolant Temperature as a function of time as measured through the PCM and with the additional T/C.

Fuel Rate changes by approximately 10%. Notice that the mean value is not one because we have used an approximate value for the fuel density (the Coriolis meter provides Fuel Rate in pounds/hour). The ratio for Pedal appears to depend on engine speed and may be related to the transfer function of the servo operating the engine pedal. The +/- 10% variation in the ratio associated with Torque (Load% for the PCM data) may be related to the fact that Load% is an estimate of torque based on fuel normalized by the rated torque. The ratio for the Intake Manifold Air Temperature shows a 5% variability. The rapid fluctuations observed in this trace are due to the fact that the resolution of the CAN temperature data is 1 degC. Additionally, the response time of the thermistor is slower than that of the thermocouple. As a consequence, some of the fluctuations in the trace arise from the time lag between sensing devices. Both effects can be seen in Fig. 7 in which the CAN Engine Coolant temperature plot is overlaid on that derived from the Dyno data.

The ratio between Torque measured by the dyno and that inferred by the PCM is further complicated by the type of control strategy used in this engine, which is based on speed (Governor) not on torque as commonly used in passenger applications. In this engine, Pedal is taken as a request for holding a certain engine speed. The PCM then commands the amount of fuel that produces enough torque to hold that speed. Figs. 8 and 9 show the measured relationship between pedal position and engine speed and between torque and fuel flow. Because of the almost flat response of Pedal on Torque, it may be difficult to rely on the Pedal Position parameter as a diagnostic signature. However, when the maximum engine output is reached at a given speed, the other two parameters broadcast on CAN (Desired Speed and Load%atSpeed) assume their maximum value. The deviation between desired and actual speed and between estimated Load% and the calibration value may be useful for inferring a shift in engine performance and as a diagnostic indicator that the engine operating conditions are outside the normal envelope.

Notice that the PCM controls the amount of fuel injected by commanding the opening and closing of the injectors and by changing the Injection Pressure (that is, the high pressure oil line) by means of the PWM of a bleed valve to achieve fast response. The duty cycle of such valve is not available on CAN but can be obtained through the scan tool since monitoring whether the actuator is pegged to either one of its control limits is the traditional method for identifying malfunctions. This is an example that other useful parameters are available through a different communication protocol but potentially reserved for OEM use.

FAULT SEEDING

We discuss below the effects observed with seeded faults. We first review the case when the gain of the Injection Control Pressure Sensor is altered. To quantify effects in the engine operating parameters, we use mean values calculated over 20 s at each step in the test sequence. In this way we can readily compare the sensitivity of a parameter to the perturbation level.

Fig. 10 shows composite plots of mean values of selected

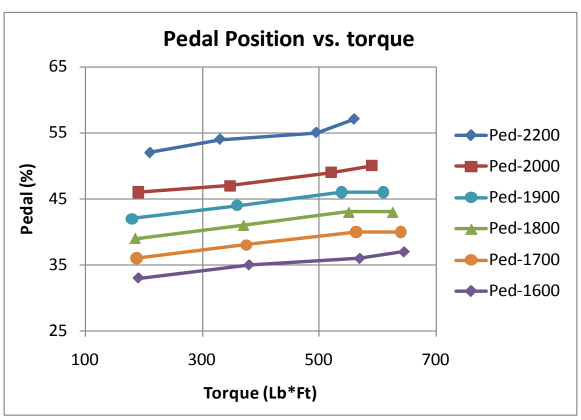

Figure 8. The Pedal% is plotted against Torque.

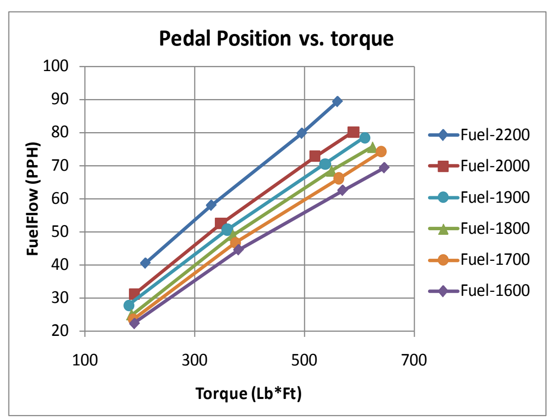

Figure 9. The Fuel Flow is plotted as a function of torque.

CAN and Dyno measurements plotted according to the order with which the points in the test sequence were stepped through as indicated in Table 3. The points at low torque have been omitted in these tests. The data refer to four replicas of the test sequence, one without the fault (Gain =1) and three with gain changes of x0.94, x1.04, x1.15, respectively, as indicated in the legend. Notice that in this experiment, torque is not controlled and the pedal position is set to the mean value found in previous tests under speed/control mode. However, not always the same torque value is reached after engine restart likely because of instability in the servomechanism that actuates the engine pedal.

The data in Fig. 10 show that there is no apparent change in Injection Control Pressure since the PCM is able to compensate for the different sensor reading by means of the pressure control valve. No changes are seen in the commanded fuel, thus, Load% does not change since it is calculated from speed and fuel. On the other hand, a change in fuel delivered to the combustion chamber has occurred since a higher/lower control pressure translates into a higher/lower quantity of fuel injected in the cylinder. Notice that if the sensor is skewed high (gain x1.15, for instance)

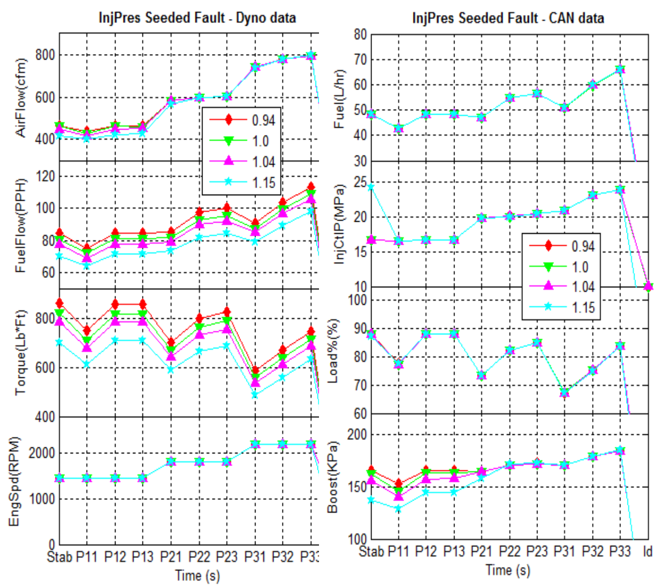

Figure 10. Mean values of engine operating parameters at different speed/torque points are plotted in the order with which the data were acquired during a test sequence similar to that of Table 3. Each plot corresponds to a test during which gain of the Injection Control Pressure sensor was altered by a factor indicated in the legend. For these tests the dyno was operated in "open loop"; torque is only measured but not held constant, while the Pedal was fixed

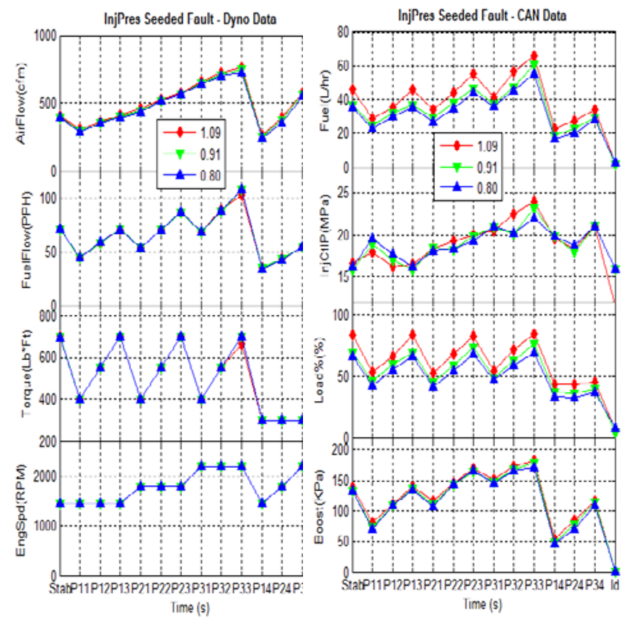

Figure 11. Mean values of engine operating parameters at different speed/torque points as given in Table 3 without the low torque points. The gain change applied to the Control Pressure is indicated in the legend. These tests were carried out with the dyno operating in speed/torque control mode.

the PCM decreases the injection pressure, thus, the quantity of injected fuel decreases. Indeed, the engine torque output measured by the dyno changes proportionally with fuel since the dyno is not trying to control torque. The fuel flow measured by the external instrument (the Coriolis fuel meter) confirms that fueling has changed.

The plots in Fig. 11 show the opposite effect. In this case Torque is kept constant by the dyno. When the PCM adjusts the injection pressure by means of the bleed valve to correct for the pressure shift indicated by the skewed sensor, the engine output changes but the dyno corrects for the torque change by means of the throttle. Thus, the dyno cell instruments do not detect any change in either torque or fuel, but a small shift in Pedal can be observed (Fig. 11a). The

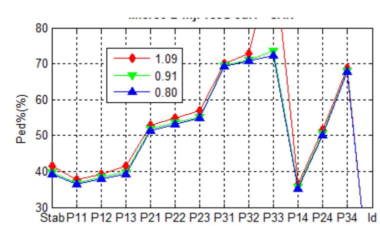

Figure 11a. Plots of the CAN Pedal% for the same tests illustrated in Fig. 11.

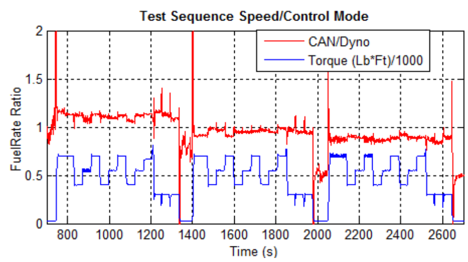

Figure 12. The ratio of the CAN Commanded Fuel over the Dyno Fuel Flow value, after correction for the different units, is plotted as a function of time for same tests analyzed in Fig. 11. The Dyno Torque value is also shown as a marker of the step progressions as a function of time.

PCM data, however, show changes both in Fuel and Load % due to the Pedal correction caused by the dyno controller. The plots in Fig. 11a show that the Pedal change is very small (of the order of 1 to 2%) because Pedal is insensitive to Torque within a certain range as indicated in Fig 8. If at that speed the engine is not able to produce enough torque, the pedal value climbs up toward 100%. For instance, this is seen happening at the third torque step at 2400 RPM.

Fig 12 shows a plot of the ratio of the CAN Fuel over the

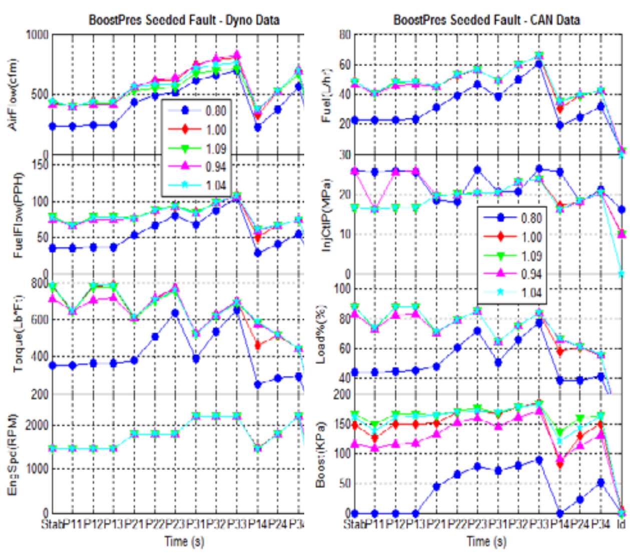

Figure 13. Plots of mean values of engine operating parameters when the Boost Pressure sensor gain was altered by a factor indicated in the legend. The engine torque was not controlled by the dyno,

Dyno Fuel Flow value, after taking into account the difference in units. The Dyno Torque trace is also superimposed as a marker of the step progression. The ratio is seen to change in steps for each test repeat reflecting the change in gain for the Injection Control pressure sensor. The ratio can be used to quantify the effect of the seeded fault.

The effect of changing the Boost Pressure sensor gain is illustrated in Figs 13 and 14.

Fig. 12 shows the same type of plots reported in Figs. 10 and 11 to describe the effects caused by altering the gain of the Boost Pressure sensor. In this case, the engine torque was not controlled by the dyno but was free to change.

Similarly to the case of the Injection Control pressure, the PCM tries to compensate for the shift in pressure perceived through the skewed sensor by changing the amount of exhaust that is diverted from the turbocharger by means of the wastegate valve. The change in control action can be observed by means of the Scan Tool. Thus, if the sensor reads low, the PCM directs more exhaust into the turbo and the intake air flow is observed to increase (case of gain x0.94). Torque is not expected to change as long as fuel is not affected. However, the PCM may infer from the lower boosting action that the intake flow has decreased with the potential for increasing exhaust gas temperature above the safe operating limit for the turbocharger. Thus, it may cut fuel as a precautionary measurement, as observed at 1450 RPM. Oscillations in Injection Control pressure are also observed in this regime and the boost start fluctuating. More dramatic changes are observed when the sensor gain is changed by x0.8. At low engine speed the PCM cannot compensate for such a large boost decrease, thus, it decreases fuel, which in turns decreases the turbo performance and the intake air flow decreases.

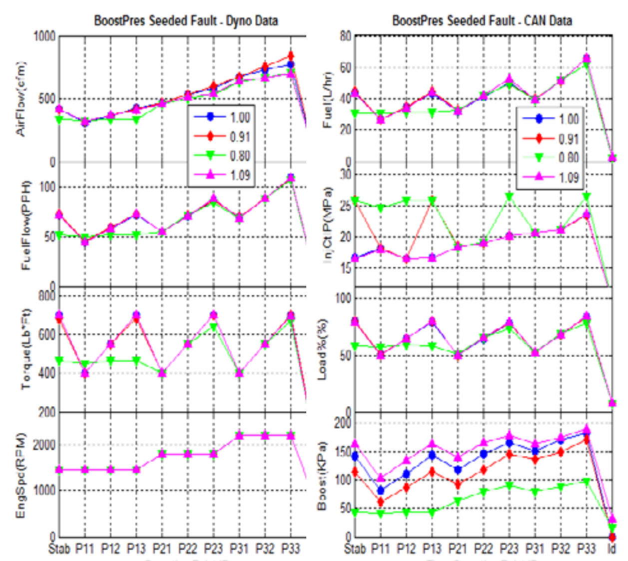

Figure 14. Data obtained when the dynamometer operates in speed/torque control mode for different perturbations of the Boost Pressure sensor. The sensor gain was multiplied by a factor indicated in the legend.

As long as the PCM does not react to the perceived boost change by cutting fuel, the engine response to this type of fault would not change even if the engine is operated at constant torque. The plots in Fig. 13 support this interpretation since the Boost perturbation as seen in the CAN data does not seem to be affecting other operating parameters, as least for small gain changes. At a gain change of x0.8, however, the low fuel and torque data are consistent with the PCM derating the engine. The changes are less pronounced in these experiments than in the previous ones because they were carried out at lower torque.

Conclusions

We have shown how the torque output of the engine was modified in a repeatable way by changing the calibration of sensors that are used by the PCM to control the engine. We have described two cases: one in which we have perturbed the fuel delivering system by skewing the calibration of the injection control pressure, the other in which the air induction system has been perturbed. In both cases, the PCM detects a pressure setting difference from that derived by the calibration value at the speed/load corresponding to the pedal position and attempts to reach the desired set point by adjusting the corresponding actuator. We have shown that with small perturbations in the transfer function of these sensors it is possible to either increase or decrease the engine output by 10% to 20%. Additionally, we have shown that the change in engine output can be achieved in progressively increasing steps which is useful in assessing the sensitivity of models. The ability to detect small output changes is the basis for developing an on-board monitor of abnormal shifts in engine performance associated with incipient component failures.

With this set-up it is possible to build a knowledge base of observable symptoms of abnormal operating conditions. Additionally, relying on different instrument and production sensors and different data acquisition methods, it is possible to evaluate the type of data that an aftermarket vehicle data recorder could easily access and determine whether such information is sufficient for detecting incipient malfunctions reliably, even if the specific part that is failing cannot be pinpointed with on-board monitors. Limitations and potential pitfalls associated with on-board data processing capabilities can also be similarly addressed.

While the dynamometer setting is free of the several noise factors present in the field (transient operating conditions, vehicle-to-vehicle variability, normal part aging, environmental conditions of temperature, humidity, road roughness, fuel quality, and driver behavior), we have argued that it is a valuable test bed for collecting a broad set of information with which detection schemes and models can be tested. Additionally, it is useful in developing the methodology with which data needs to be acquired and processed, especially when pursuing development of empirical models based on machine learning, which require a large number of repeated measurements.