

Diagnosis and Prognosis of Fuel Injectors based on Control Adaptation

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ABSTRACT

Spark Ignition Direct Injection (SIDI) technology enables better fuel economy and tail pipe emissions in vehicles equipped with gasoline engines. The SIDI technology depends on the ability of the system to deliver fuel at high pressure directly into the combustion chamber, hence making the fuel injectors key subcomponents. Reliable performance of fuel injectors is vital as it directly relates to the operability of the vehicle, and hence customer satisfaction in case of failure. It, therefore, becomes very important to devise a scheme that can effectively diagnose and prognose such a component. In this article, algorithm development for diagnosis and a pathway to prognosis of fuel injectors is presented. We do not propose any additional sensing capability, and make use of what is available in most of the production vehicles today across the industry. In particular, the control adaptation of fuel control and the associated diagnostics that are mandated by regulators are employed to generate schemes for fault detection, fault isolation, and fault prediction. Results are presented from vehicle test data that allow development of such a scheme for fuel injectors.

1. INTRODUCTION

Stricter emission regulations and increasing fuel economy requirements have been amongst the key driving forces that have led the automotive industry to constantly improve the efficiency of gasoline engines, and also innovate to reduce harmful exhaust gas emissions. Corporate Average Fuel Economy (CAFE) is the primary vehicle mileage standard in the United States. From 1990 to 2010, the CAFE standard for the passenger vehicle remained fixed at 27.5 mpg. However, the CAFE standard has been changing rapidly in recent years, with its value reaching 35.5 mpg in 2016 and increasing to

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54.5 mpg by 2025 (Ferguson & Kirkpatrick, 2015). Following the stricter requirements, the emission level of current internal combustion engines has decreased to about 5% of the emission levels that were prevalent 40 years ago (Ferguson & Kirkpatrick, 2015).

Up until 1990s, Port Fuel Injection (PFI) Engines reflected state of the art for production gasoline engines (Çelik & Ozdalyan, 2010). Advancement in computer-based control made it possible to deliver gasoline precisely through solenoid-based fuel injectors, just upstream or at the back of each cylinder's intake valve. The fuel then mixes with the incoming air, and gets pulled into the combustion chamber when the intake valve opens. Combined with oxygen sensors mounted on the exhaust, the computer is able to achieve very accurate control of desired air-fuel ratios. PFI engines, however, still could not overcome the following challenges (Takagi, 1998):

- degradation in fuel economy due to pumping losses during part load operation,
- knock limited output performance,
- wall wetting or formation of fuel puddle in the manifold during cold engine start resulting in excessive Hydrocarbon emissions.

Increasingly tighter fuel economy and emission regulations prompted the herald of spark ignition direct injection (SIDI) engines into production. In SIDI engines, fuel is injected directly inside the combustion chamber at high pressure during the compression stroke, reducing wall wetting and hence improving cold start Hydrocarbon emissions. A pictorial difference of Port Fuel Injection and Direct Injection is shown in Figure 1.

Direct Injection has many advantages (Zhao, Lai, & Harrington, 1999; Smith & Sick, 2006), for example, it:

- reduces throttling loss of the gas exchange by stratified and homogeneous lean operation,

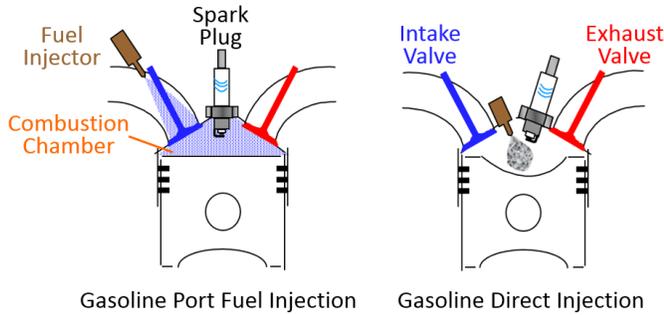


Figure 1. Schematic of Gasoline Port Fuel Injection and Gasoline Direct Injection Systems

- enables higher thermal efficiency by stratified operation and increased compression ratio,
- decreases the fuel consumption and CO₂ emissions,
- lowers heat losses,
- enables fast heating of the catalyst by injection during the gas expansion phase,
- increases performance and volumetric efficiency due to cooling of air charge, and
- enables better cold start performance.

Compared with conventional Spark Ignition engines, SIDI engines utilize lean-burn-based stratified charge mixture, increasing fuel economy by up to 25%, depending on the test cycle (Zhao et al., 1999). The SIDI engines also provide a 10% improvement in power output while simultaneously reducing the cold start unburned HC emissions by approximately 30% (Takagi, 1998). SIDI engines have allowed the reduction of pumping loss, knock, and intake port wall wetting, the resolution of which was a long-cherished wish of combustion engineers.

There is an increasing trend towards the adoption of SIDI engines in the North American market. According to Information Handling Services (IHS), there is a decreasing trend in the production forecast of PFI engines, and they are being gradually replaced by the SIDI engines. The total number of engines running on PFI technology will reduce down to 4 million by 2023, as compared to 13 million engines that will feature SIDI technology according to the production forecast generated by IHS (see Figure 2). Hence, more and more vehicles will be equipped with SIDI engines in the future. The ability to deliver highly pressurized fuel directly into the combustion chamber is the key enabler for the SIDI engines. It is, therefore, imperative that the fuel delivery system of an SIDI engine can operate without failure. Failure in the fuel delivery system of SIDI engines can cause customer frustrations, costly road side assistance (including vehicle towing), and negatively impact the perceived quality of the automotive manufacturer.

GM launched OnStar™ Proactive Alerts service™ on selected

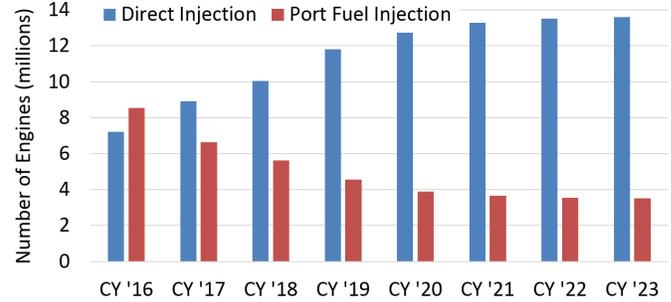


Figure 2. Production Forecast of Direct Injection & Multi-point Fuel Injection Engines in North America (Source IHS)

vehicle programs and selected vehicle components in Model Year 2016 under its strategic initiative to develop Vehicle Health Management (VHM) technologies. The OnStar™ Proactive Alerts service is designed to provide early warning to customers in case a component failure is impending, thereby turning emergency repair services into scheduled maintenance events. More advanced VHM technologies are to be developed under this initiative. The fuel delivery system of an SIDI engine is critical to a given vehicle's driveability, and fuel injectors are amongst its key components. It is, therefore, highly desirable that their failure is prevented, and a timely warning be issued in case of imminent failure, so that they can be timely serviced. In addition, billions of US dollars are spent by the automotive industry towards covering the warranty costs and most of the fault identification and isolation techniques involve offline troubleshooting by the service technician based on the data available from the vehicle at that very instant (Lanigan, Kavulya, Narasimhan, Fuhrman, & Salman, 2011). Limited information sometimes leads to erroneous parts replacements causing unnecessary increase in warranty costs and customer inconvenience. Much of the on-board diagnostics today, especially related to powertrain, have been developed with a focus of meeting the regulator requirements and not so much from a service perspective. This article provides the development of prognostic technologies for fuel injectors by detecting degradation in their performance with a focus to identify the correct problem by leveraging the historic data, and fixing it right the first time. The problem is quite challenging if the sensing ability is limited to what is available in the production vehicles today without adding any additional sensing capability to aid our quest. No prior literature exists, to our knowledge, that provides any development towards prognosis of fuel injectors for SIDI system.

The article is organized as follows. Section II describes the operation and control of SIDI high pressure fuel delivery system, and focuses on the operation and control of fuel injectors. Section III describes the possible faults that occur in fuel injectors along with experimental cases to study these faults. Section IV describes the fault identification, isolation, and prognostics algorithm that is developed based on the in-

sights gained from Section III. We conclude the findings of our study in Section V.

2. HIGH PRESSURE FUEL DELIVERY SYSTEM DESCRIPTION

A typical SIDI system is shown in Figure 3 for a four cylinder application. In SIDI systems, gasoline is injected directly into the combustion chamber. This requires gasoline to be at high pressure which is achieved in two steps. First, the in-tank electric fuel pump delivers fuel from the tank to the inlet of the high pressure fuel pump. The high pressure fuel pump then compresses, and pushes the necessary amount of fuel into the fuel rail, generating and maintaining the required pressure. The high pressure fuel pump increases the fuel rail pressure from a pump inlet line pressure of 0.3 to 0.5 MPa to a range of 1 to 20 MPa. Fuel injectors are connected to a common fuel rail and remove fuel from the fuel rail with each injection event, resulting in a decrease in fuel rail pressure. Each pumping event of the high pressure fuel pump, on the other hand, adds fuel to the fuel rail increasing the pressure. The pressure profile of the fuel rail, therefore, oscillates around a pressure set point.

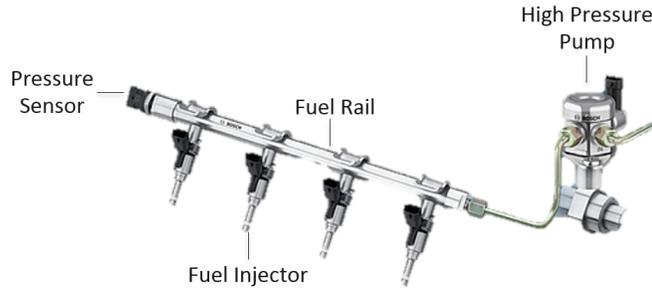


Figure 3. Schematic of High Pressure Fuel Delivery System

A cross sectional view of a typical fuel injector (courtesy of Bosch) is shown in Figure 4. The fuel injector is driven by a solenoid, where a tension spring forces the plunger to block off the fuel pathway through the injector when the solenoid is powered off. When the solenoid is powered on, the plunger is attracted towards the electromagnetic coil, allowing the fuel to pass through the injector and exit at the injector tip. The time duration of injector opening, also called injector pulse width, is directly proportional to the amount of fuel that passes through it at a given fuel rail pressure. Injector mass flow can be modeled as the following modified Bernoulli equation, which represents the flow through an orifice (Merritt, 1967),

$$\dot{m} = \rho A C_d(\lambda) \sqrt{\frac{2|\Delta P|}{\rho}} \quad (1)$$

where ρ is the fuel density, A is cross-sectional area of the

orifice, ΔP is the pressure differential between the fuel rail and engine cylinder during intake stroke, and the discharge coefficient C_d is given as:

$$C_d = C_{d_{max}} \tanh\left(\frac{2\lambda}{\lambda_{critical}}\right) \quad (2)$$

The dimensionless flow number λ is given as:

$$\lambda = \frac{d_h}{\nu} \sqrt{\frac{2|\Delta P|}{\rho}} \quad (3)$$

where, d_h is hydraulic diameter and ν is the kinematic viscosity.

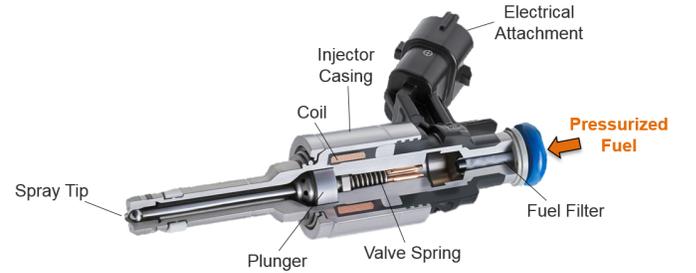


Figure 4. Cross-section of Fuel Injector (Bosch)

2.1. Integrated Control and Diagnostics of High Pressure Fuel Delivery System

A typical schematic of integrated fuel delivery system is shown in Figure 5. Given the engine speed, throttle position, and the associated air intake into the cylinders, Engine Control Module (ECM) continuously calculates the amount of fuel required to be injected into the cylinders for combustion at stoichiometry conditions (14.65 parts air, and one part gasoline). Hot gases that are the byproduct of combustion are pushed out into the atmosphere through the exhaust system that includes one upstream oxygen sensor (pre O₂), a three-way catalytic converter, and a downstream oxygen sensor (post O₂). The upstream oxygen sensor determines how much oxygen is present in the combustion byproduct, and passes this information to the ECM. Primary fuel control scheme, described in more details below, adds more fuel if excessive quantity of oxygen is detected by increasing the injector pulse width. Fuel is taken away if less oxygen is detected by reducing the injector pulse width. A secondary fuel control scheme fine tunes the amount of fuel delivered, based on the performance of the catalyst as discussed below in more detail. As the fuel leaves the fuel rail through the injectors, the pressure in the fuel rail decreases. The pressure sensor in the fuel rail measures the rail pressure and passes this information to the ECM, which then commands the opening and closing timing of the solenoid valve on the high pressure fuel pump to ensure that the rail pressure is maintained at the de-

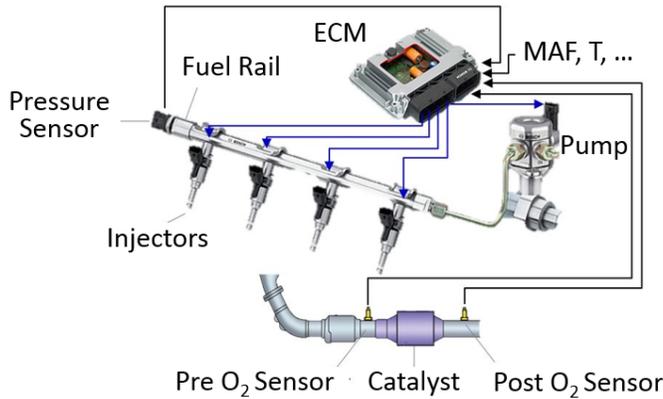


Figure 5. Integrated Control of Fuel Delivery System

sired value. The following provides a detailed description and various elements of the fuel control system, which is captured in a schematic in Figure 6.

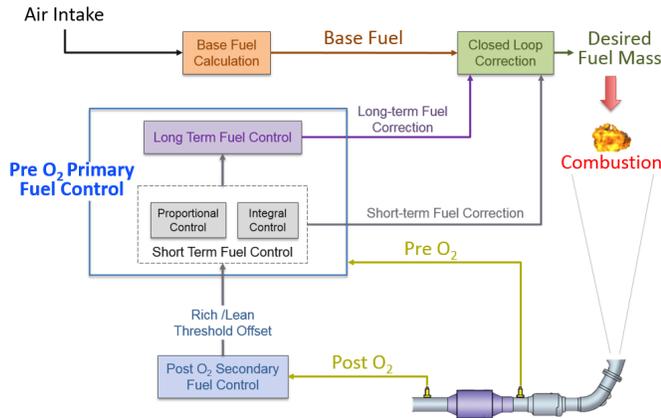
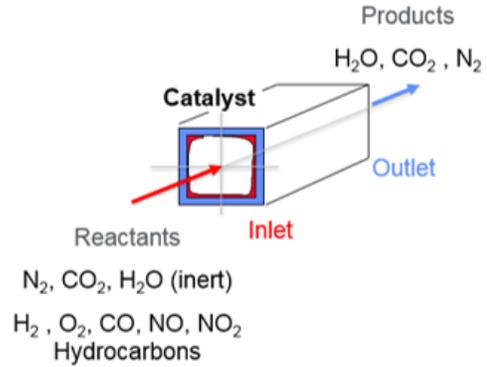


Figure 6. Fuel Control Schematic

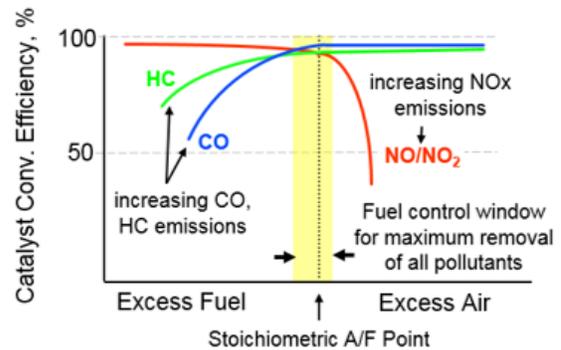
2.1.1. Primary Fuel Control

The closed-loop fuel control algorithm attempts to provide a stoichiometric air fuel (A/F) exhaust gas supply to the catalytic converter. Typically, the combustion byproducts of SIDI engines consist of H_2 , O_2 , H_2O , CO , CO_2 , NO , NO_2 , and unburnt hydrocarbons as shown in Figure 7. Performance of a typical three-way catalyst is also shown in Figure 7, where NO_x are reduced and, CO and unburnt hydrocarbons are oxidized. The efficiency of the catalyst to reduce NO_x improves when more fuel is present compared to air. The efficiency of the catalyst to oxidize CO and unburnt hydrocarbons, however, increases when excess air is present. As shown in Figure 7, there is an optimum window around stoichiometry where maximum percentage of pollutants are removed.

O_2 sensor placed prior to catalytic converter provides the necessary feedback signals for the primary fuel control, and is



Typical Performance of a Three-way Catalyst



Key Chemical Reactions

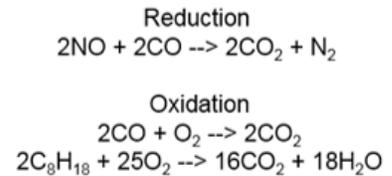


Figure 7. Operation of a Three-way Catalyst

critical to maintaining the A/F ratio at stoichiometry for optimal overall tailpipe emissions. The control system generates a dithering signal that forces the O_2 sensor signal ‘rich’ (by adding more fuel) when it currently indicates ‘lean’, and forces it ‘lean’ (by cutting off fuel) when it indicates ‘rich’. This constant toggling of the O_2 sensor output is intended to maintain the exhaust average A/F ratio at stoichiometry, and to ensure efficient performance of the catalytic converter. As mentioned earlier, the efficiency of catalytic converter to remove NO_x is high when more fuel (rich condition) is present, and it is more efficient in removing CO and unburnt hydrocarbons when excess air is present. Toggling continuously between lean and rich conditions also ensures that the pollutants are eliminated with good efficiency on the average as per the requirements of environmental regulations. This subset of the primary closed-loop fuel control algorithm, known as short-term control correction, also helps to identify the optimal system delays and gains to maintain the best possible

fuel control, i.e. maintains at stoichiometry with minimum variations. The long term multiplier (LTM) begins to learn once the integrator has moved outside a calibrated operating range, essentially exchanging the offset in the short-term integrator to the LTM value. Figure 8 presents a graphical representation of the above description.

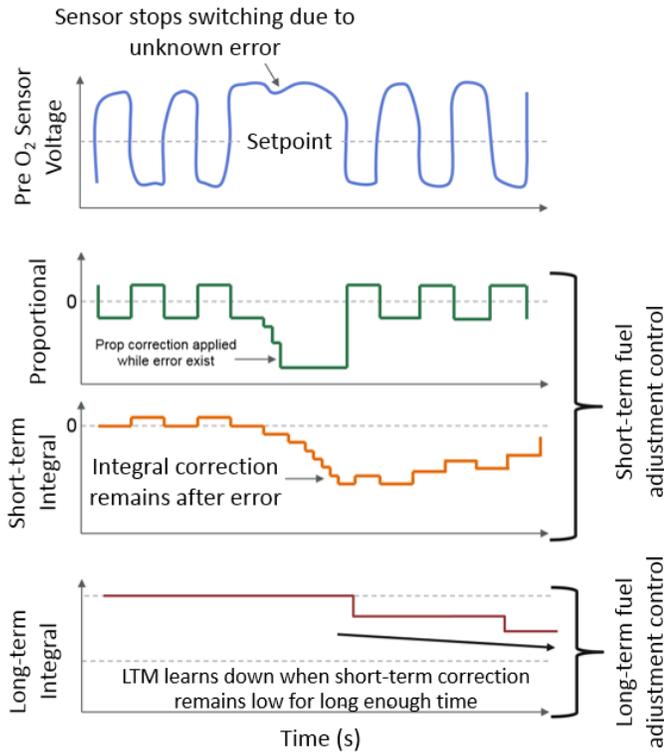


Figure 8. Short-term and Long-term Fuel Control Adjustment

2.1.2. Secondary Fuel Control

Secondary fuel control has significantly less authority than primary fuel control but is just as critical for the overall emissions performance. The post-catalyst O₂ sensor has the distinct advantage of being able to “see” the post-catalyst exhaust stream, and thus provide feedback regarding exhaust stoichiometry. Maintaining A/F stoichiometry is critical to optimizing catalyst conversion efficiency. Secondary fuel control, therefore, provides an important fine-tuning mechanism for the overall fuel control and emissions performance. This control loop improves the robustness of the system by correcting slight shifts in the stoichiometric operating point that may occur over the life of the vehicle. The control structure is similar in design as the short-term control correction in that there is a proportional and an integral term. The overall gain of the system is very damped to band limit the response, and to make only slight offsets in the control. Rather than learn a correction factor, the post system learns an offset to the stoichiometric set-point used in the short-term system, as

depicted in Figure 6. This offset can learn in the ‘rich’ or ‘lean’ direction based on the output of the post oxygen sensor being either above (rich) or below (lean) the target value. A graphical representation of the above description is given in Figure 9.

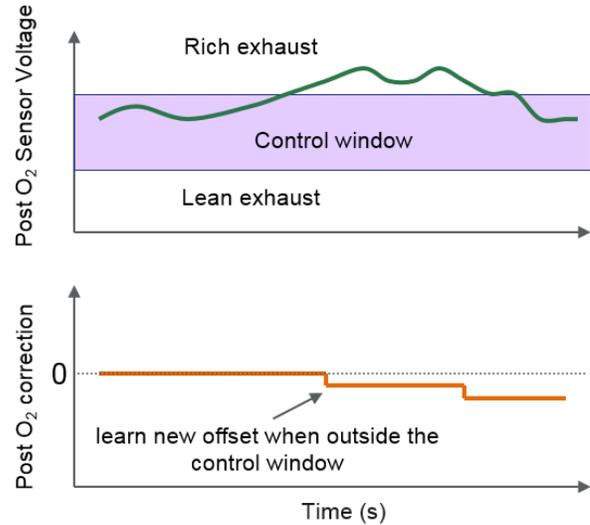


Figure 9. Post-O₂ Fuel Control Adjustment

2.2. Relevant Diagnostics

Direct fuel metering on SIDI engines is very expensive, and is seldom practiced on any of the commercially available engines. It is, therefore, not possible to draw a direct conclusion about the performance of a single fuel injector in any given engine based on direct fuel metering. Any information relevant to the combustion process, hence, becomes important so that right conclusions can be drawn. One such relevant information about the combustion process is provided by Air Fuel Imbalance Monitor (AFIM) diagnostic which is mandated by the regulators. The purpose of the AFIM diagnostic is to detect a rich or lean cylinder-to-cylinder air fuel ratio imbalance in a given engine bank. A rich or lean cylinder air fuel imbalance will result in a pre-O₂ sensor signal frequency higher than typical for that bank. Figure 10 presents typical pre-O₂ sensor signals for increasing level of imbalance.

Another piece of relevant information is engine misfire. Government regulations require engine misfire to be detected on any given cylinder. An engine misfire causes the power in one or more cylinders to drop. An ideal engine with no misfire would result in zero deceleration or jerk from one combustion event to the next. Misfire may be due to a vacuum leak, clogged fuel injectors, worn or fouled spark plugs, bad spark plug wires, or weak ignition coil. It is plausible that a clogged injector will cause the LTM to indicate lean conditions, while registering continuous or intermittent misfire for the relevant cylinder at the same time. Additionally, it is

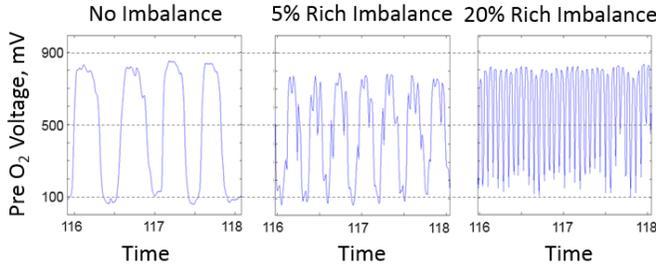


Figure 10. Pre-O₂ Sensor Voltage Characteristics with Increasing Levels of A/F Imbalance

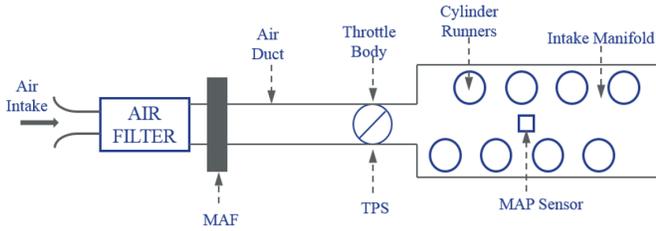


Figure 11. Air Intake System

important to gather information related to the air measurement, as variation in LTMs from the nominal can happen because of erroneous air measurements (or induction leak). Typically, in vehicles equipped with gasoline engines, a Mass Airflow (MAF) sensor measures the air mass flow rate into the air manifold, and is mounted before the throttle body, towards the air filter as shown in Figure 11. Together with the throttle position, air delivered to the engine is estimated from the MAF sensor information. A Manifold Absolute Pressure (MAP) sensor mounted closer to the cylinders estimates the air intake based on the manifold pressure. Under stable operating conditions (e.g. idling, cruise) the air estimated by the MAP and MAF sensors should match closely, and the ratio between the estimation of the two should be close to unity. If the air measurement is faulty, or if an induction leak is present, the ratio between the two measurements is likely to deviate away from unity. Since both the injector faults and poor air measurements may cause the LTMs to deviate from nominal, the air measurement diagnostics can help to isolate the injector faults.

3. POSSIBLE FAULTS IN FUEL INJECTORS

The high pressure fuel injectors are designed to deliver fuel at high pressure directly into the combustion chamber, and must withstand temperatures as high as 750°C, and pressures as high as 4 MPa. The fuel delivery system ultimately relies on the fuel injectors to successfully deliver the right amount of fuel into the combustion chamber at the right time. Failure to successfully perform its designed operation will result in reduced engine performance, engine damage, and even com-

plete loss of propulsion. Some of the common injector wear and failure observed in the field are summarized in Table 1.

Table 1. List of Common Faults in Fuel Injectors Experienced in Field

Failure Parameters	Fault Manifestation
Injector plugging/clogging	Increased injector pulse width through closed-loop control system
Soot on valve seats causing improper sealing	Decreased injector pulse width through closed-loop control system
Nozzle Damage Due to Misfire	Decreased injector pulse width through closed-loop control system

Raw fuel that is left on the injector tip will oxidize, and form deposits. Needle bounce, injector leakage, and the small fuel volume between the valve seat (fuel shut off point) and the entrance to the final metering orifice of the injector (sac volume) - all can have an impact on the amount of raw fuel left on the injector tip. Rail pressure, charge motion, and injector placement determine how much of the fuel remains on the injector tip. Deposit formation is accelerated by high injector tip temperatures. Fuel has a significant impact on deposit formation. Figure 12 shows pictures of a partially plugged injector tip because of deposit formation. A completely plugged injector tip hole is shown in the top left corner of the picture, whereas a partially clogged injector hole is shown in the top right corner. A fine layer of deposit can be seen in the bottom two pictures of the same injector tip. These deposits are enough to reduce fuel flow by 7%, in addition to disrupting the spray pattern of the injected fuel, and causing a loss in combustion efficiency.

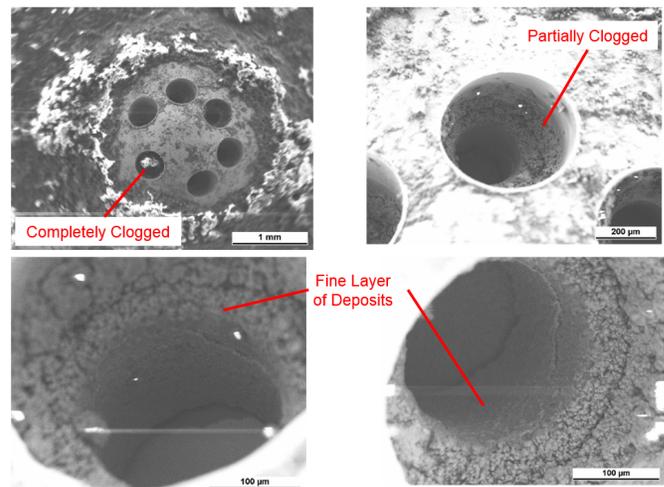


Figure 12. Field Return Clogged Injector with 7% Less Fuel Compared to Nominal.

The failure modes of injector plugging and soot development on valve seat can be simulated by shortening the opening time (pulse width), or lengthening it respectively for any given injector under study. Restricting the opening time causes less fuel to be delivered per injection event than nominal, and lengthening it increases the fuel delivered per injection event when compared to nominal. To study these faults, a vehicle equipped with a 5.3 L V8 engine was employed to simulate the aforementioned faults, and was run on the dynamometer to follow the drive cycle shown in Figure 13 (top). The drive cycle comprised of 5 minutes of FTP-75 drive cycle followed by one minute of cruise at 45 mph, which was then followed by one minute of vehicle idling. We remark here that the same learnings could be obtained by following the complete FTP drive cycle and is not limited to the specific drive cycle discussed above. The vehicle was first driven without any simulated faults, and long term control gains for injectors were logged. Following the data collection for the nominal or no-fault case, the pulse width of all the injectors on Bank 1 was reduced by 15% under all conditions, and the vehicle was driven under the same drive cycle as shown in figure 13 (top). The pulse width of all the injectors on Bank 1 was further reduced by 30%, and data was collected under the same drive cycle.

The results are summarized in Figure 13 (bottom). It can be seen that when the fuel is restricted in Bank 1, the control system responds by increasing the long term control gain which in effect opens all the injector longer, when compared to the nominal, delivering more fuel and hence compensating for the lost fuel due to the restriction imposed on the injectors. On the other hand, when the injectors in Bank 1 are made to deliver more fuel than nominal (rich) by increasing their pulse widths, the control system responds by decreasing the long term control gain which in effect opens all the injector for a shorter duration, compensating for the additional fuel delivered by the injectors in Bank 1. The LTMs are therefore a useful indicator to track the shifting of the injectors. A new set of experiments were conducted to study the effect of a single injector, while maintaining the same drive cycle as shown in Figure 13 (top). The injector in cylinder C of the engine (closest to the exhaust in the V8 configuration) was first made to shift lean by restricting its opening duration by 30% across all operating conditions, and the LTMs were logged. The injector in cylinder C of the engine was then made to shift rich by increasing its opening duration by 30% across all operating conditions, and the long term control gains were again logged. The results are summarized in Figure 14. As seen earlier where the entire Bank 1 was shifted, when the injector in cylinder C is restricted, the control system responds by increasing the LTMs in order to compensate for the restriction. When the injector in cylinder C is made to deliver more fuel than nominal (rich), the LTMs decrease and open the injector for a shorter duration in order to compensate for

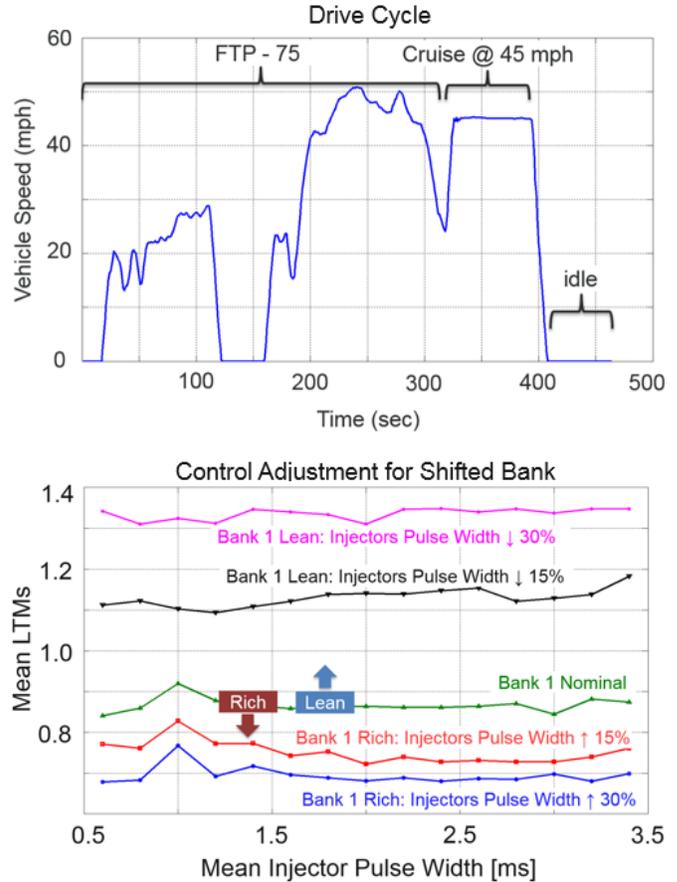


Figure 13. Drive Cycle for Injector Fault Testing (top), and Control Adjustment for Shifted Bank 1 Across Various Injector Pulse Widths (bottom).

the excess fuel delivered by the injector in cylinder C. It is interesting to note that when only one injector is shifted, as opposed to a complete Bank, the effect on LTMs is more pronounced at a range of injector pulse widths from 1.25 ms - 2.5 ms. At higher injector pulse width, or at lower injector pulse width the LTMs do not compensate as much for the deviation of injector from the nominal behavior. It is worthy to note here that while LTM can prove to be a useful indicator to identify injector shift (clogging or soot deposition) in a cylinder bank, it does not help identify a particular injector. In a situation when only one injector is shifted, the exhaust system might sense an air fuel imbalance (discussed above) implying that some cylinders could be having an air fuel ratio that is different than the rest. Due to poor fuel delivery (less fuel), the cylinder with shifted injector may also experience misfire as mentioned above. Together, all of this information can be quite useful in identifying an injector that has shifted from the nominal. For a proof a concept, the same vehicle as above, was employed for testing. The injector in the cylinder C was shifted lean by 30%, and the vehicle was driven on a dynamometer to follow the same drive cycle that is shown

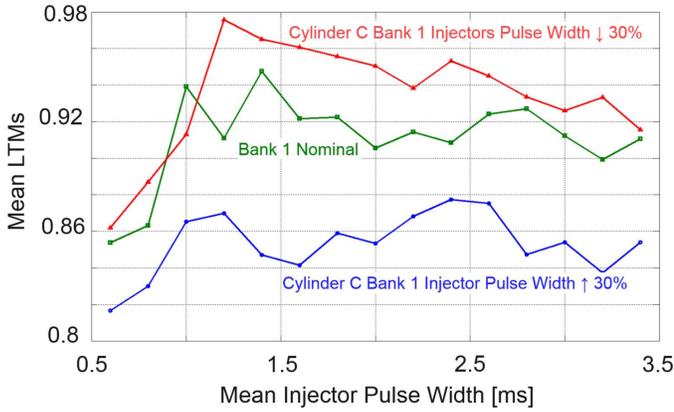


Figure 14. Control Adjustment for Shifted Injector in Cylinder C Across Various Injector Pulse Widths.

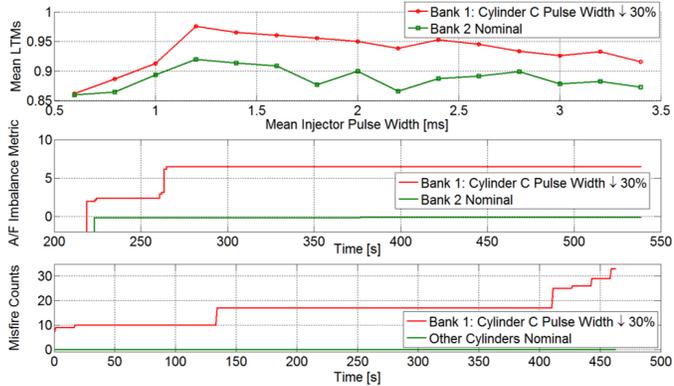


Figure 15. Shifted Injector Contributing to Change in Control Adjustment, Air Fuel Imbalance, and Misfire.

in Figure 13. The results are captured in Figure 15, where the control adjustments are seen to increase for Bank 1 (that contains cylinder C) in comparison to Bank 2 (un-faulted) in order to compensate for the restricted fuel injector. Air fuel imbalance metric for Bank 1 (faulted) can also be seen to increase in comparison to Bank 2 (un-faulted). Also shown at the bottom plot of Figure 15 is the misfire count for all the cylinders. It is quite evident that none of the cylinders, other than cylinder C, experiences a misfire, thus indicating that the fault was introduced in cylinder C.

4. FAULT ISOLATION, IDENTIFICATION, AND PROGNOSIS

Based on the physics, closed-loop control of fuel injectors, and the associated diagnostics, and signals related to combustion and air intake presented in previous sections, fuel injector faults that carry warning signs can be tracked and isolated, and the driver can be warned of a possible failure or loss in performance ahead of time. A flow chart of such a fault isolation and identification scheme is presented in Figure 16. If the LTMs are seen to deviate consistently away from the nomi-

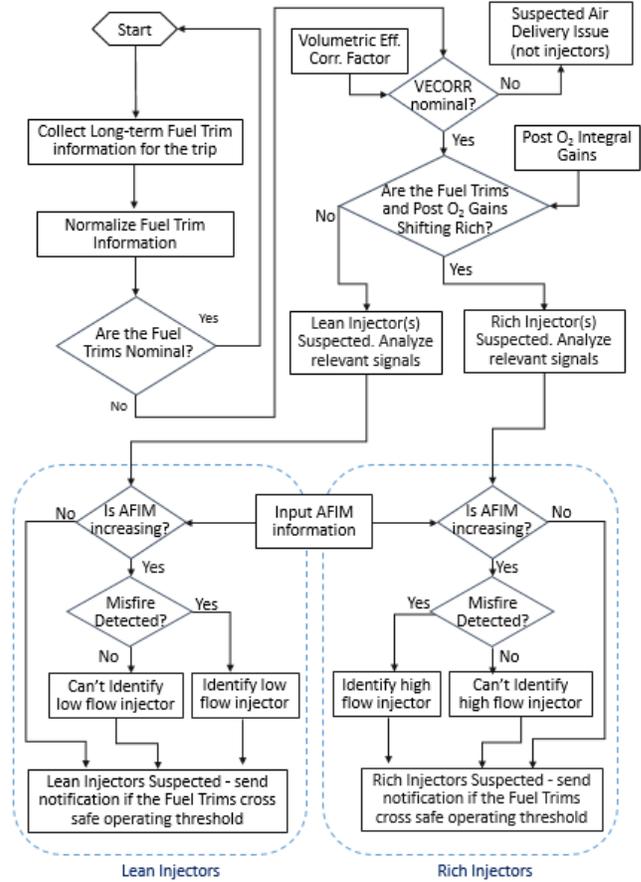


Figure 16. Flow Chart of Injector Fault Isolation.

nal, various operating conditions are assessed to determine the cause for the shift. If the fuel pressure is low from the fuel rail, the condition may indicate a failure mode upstream in the fuel delivery flow path aside from the fuel injectors that is causing an LTM shift. That is, upstream fuel flow faults may reduce the certainty of determining a specific fuel injector fault. If the fuel pressure is within an acceptable range, the volumetric efficiency correction factor is examined to ensure the accuracy of air measurement system. As mentioned in the previous section, this factor should be close to unity at stable conditions; significant deviations from unity will indicate an erroneous air measurement system or an induction leak that can cause LTM shift not allowing the isolation of injector fault. In other words, air flow faults reduce the certainty of determining a specific fuel injector fault. If the volumetric efficiency correction is found to be nominal, data collected from post O_2 gains are compared with the LTMs. If the LTMs suggest lean conditions, the post O_2 gains must not indicate rich conditions. Similarly, if the LTMs suggest rich conditions, the post O_2 gains must not indicate lean conditions. In summary, LTMs and post O_2 gains should not indicate contradictory conditions. If, however, the LTMs indicate rich conditions and the post- O_2 gains indicate a lean condition,

there is a possibility that there is a leak in the exhaust system between the two Oxygen sensors. Once it is established that the deviation of LTMs from the nominal is indeed because of the shift in fuel delivered by injectors, the direction of LTMs shift is used to establish the injector shift. An increase in LTM from the nominal indicates injectors shifting lean that may be caused by soot (or other deposits) formation on the injector tip. A decrease in LTM from the nominal indicate injectors shifting rich that may be caused by excessive fuel delivered due to poor sealing of the injector needle. Air-fuel imbalance explained in the previous section can further help to identify a given injector or multiple injectors that may be shifted. If the air-fuel imbalance exceeds beyond a nominal value in the presence of shifted injectors, any cylinder misfire can point towards the relevant injector(s) contributing towards abnormal fuel delivery. If no misfire is detected, while the LTMs still indicate abnormal fuel delivery condition, it is not possible to identify a particular fuel injector within a cylinder bank that is causing the abnormal combustion condition. In this case, a degraded condition may still exist, and a warning message may be issued that is associated with a cylinder bank as a whole.

5. CONCLUSIONS

We studied faults in SIDI fuel injectors where an injector plugging was simulated by decreasing the commanded opening time of fuel injectors for all operating conditions. This resulted in less fuel than nominal per injection actuation, similar to the behavior of plugged injectors. Injector leak was simulated by increasing the commanded opening time of fuel injectors for all operating conditions. This resulted in more fuel than nominal per injection actuation, similar to the behavior of leaky injectors. We showed that control adaptation data collected for fuel delivery along with associated diagnostic signals of misfire, air-fuel imbalance, and air delivery revealed that monitoring of control adaptation gains can help identify injector shifting (e.g. because of plugging or leaking), and even pinpoint faulty injector under certain conditions. At the end, we summarized our studies to generate a fault isolation and identification schemes for the injectors, and discussed how it could be used towards issuing warnings for timely repair services.

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BIOGRAPHIES



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