

Formation of Intake Valve Deposits in Gasoline Direct Injection Engines

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ABSTRACT

Gasoline direct-injection (GDI) engines have a well-known propensity to form intake valve deposits (IVD), regardless of operator service, engine architecture, or cylinder configuration. Due to the lack of a fuel-washing process that is typical of Port Fuel Injected (PFI) engines, the deposits steadily accumulate over time and can lead to deterioration in combustion, unstable operation, valve-sticking, or engine failure. Vehicles using these engines are often forced to undergo expensive maintenance to mechanically remove the deposits, which eventually re-form. The deposit formation process has not been well-characterized and there is no standardized engine test to study the impact of fuel or lubricant formulation variables. To meet this need, a proprietary vehicle-based GDI-IVD test that is both repeatable and responsive to chemistry has been developed. Using a vehicle equipped with a 2.0L turbo GDI engine, the mechanisms leading to deposit formation have been studied and analyzed, and found to be a combination of engine oil, engine-wear elements, unburned fuel, and exhaust gas contaminants. The rate of accumulation was also found to be affected by engine lubricant formulation variables.

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INTRODUCTION

Gasoline engines with direct fuel injection are now well established by engine manufacturers worldwide as a means to improve fuel economy and specific output. With the addition of turbocharging and the improved cylinder scavenging at lower engine speeds, engines are being down-sized and down-speeded for ever-increasing gains in fuel efficiency. Unfortunately, the drive for greater efficiency has caused a technological hurdle in the area of intake valve cleanliness.

With fuel now being injected directly into the combustion chamber versus onto the intake valve as in PFI engines, there is no longer the washing action of the fuel and fuel-borne detergent additives to keep the intake valves free from deposits. Deposits on intake valves may now accumulate steadily over time, building until they affect engine operation, often with catastrophic consequences. [Figures 1](#) and [2](#) show cutaway models of port and direct fuel injection systems, respectively with the fuel injector position highlighted relative to the intake valve. [Figure 3](#) shows intake valves that were removed from a 2010 North American SUV with a 2.0L turbocharged-GDI (T-GDI) engine that accumulated 190,000 km of consumer service using commercial-quality fuel and lubricant. The deposit accumulation shown in this figure was consistent across all valves in twelve vehicles examined.

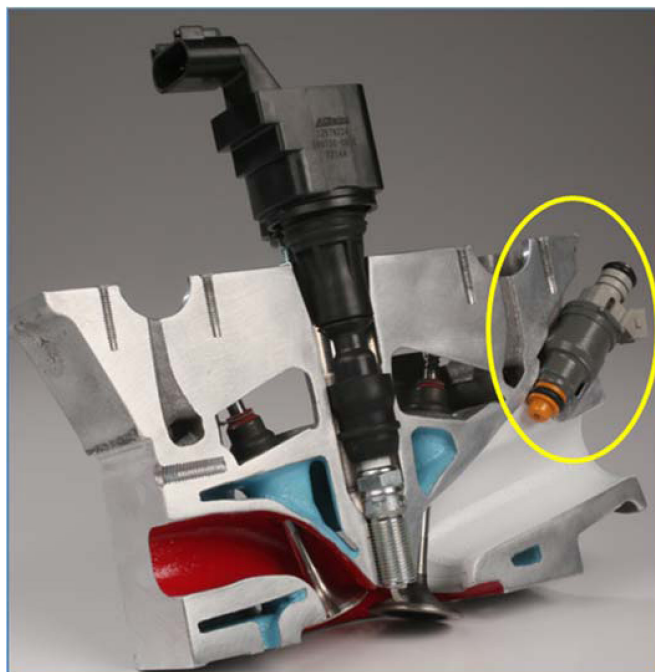


Figure 1. Cutaway Illustrating Port Fuel Injector Location

Literature review on the subject of intake valve deposits in GDI engines yield a large amount of anecdotal information from a variety of sources regarding the reason for deposit formation and how to prevent them. [1, 2, 3]. Many auto dealers offer services to clean the deposits and nearly all on-line user-forums recommend "catch cans" in the PCV circuit to collect the oil vapors that are believed to promote deposit formation. Consumer Reports magazine published a recent review where they found engines with GDI technology have improved performance and save fuel, but come with a steep price in terms of cars ending up in the repair shop more frequently [4]. In the article they cite vehicle owner and dealer service data on the build-up of carbon on the intake valves. Helping mitigate this problem, at least two automakers, have installed a set of secondary port fuel injectors in some of their models with GDI which periodically spray fuel over

the intake valves. While there are other associated benefits in terms of emissions or start-up performance, intake valve cleanliness is certainly affected by this hardware addition.

Drivability issues related to carbon buildup which can affect consumer operation occur in as few as 40,000 km and are usually seen by 130,000 km according to dealer service personnel [5].



Figure 2. Cutaway Illustrating Direct Injection

In the most severe cases the deposits can cause the check-engine, or MIL light to illuminate. With regard to drivability, one of the more common symptoms is a lack of power, especially when driving at higher speeds. Other symptoms include stalling, start-up problems, and rough running when the engine is cold. There is also a likelihood of a failed emissions test along with knocking during acceleration. In some cases, carbon buildup may cause one or more cylinder misfire codes (P030X) which will result in fuel inefficiency and overall poor performance. [6, 8]



Figure 3. Ford Intake Valves After 190K km of Service

As early as 2001 the potential durability issues associated with GDI IVD was identified by a German OEM in a 2001 patent filing. In the application they cite carbon deposits on intake valves being associated with PCV gas composition, unburned fuel constituents, blowby gas constituents, and recirculated exhaust gas [7].

OUTLINE FOR TEST DEVELOPMENT

Stated in its briefest form, the objective for this test development was to create a standardized method to produce a significant amount of IVD in a short time-duration test, with enough head-room to evaluate product efficacy. The test should be both repeatable under baseline conditions, and responsive to known additive chemistry. The following definitions add some specificity to the generalized statement, above:

1. "Short-duration" is not to exceed 16,000 km of operation in 14 days.
2. "Significant amount of deposits" is to be at least 1000 mg of IVD across eight intake valves. This metric is based on lengthy experience testing PFI-equipped vehicles for IVD performance.
3. Head-room is the ability to show an effect when the system is perturbed with additives.
4. The repeatability metric, in this case, is Coefficient of Variation (COV), and should be under 5% for repeated measures.
5. The test should be "flush and run" in that the only mechanical service between tests should be cylinder head reconditioning, along with fuel, and oil changes.
6. It would be desirable to produce a test that is vehicle-based, to include the most elements of "real world" operation.

Test Vehicle

The test vehicle chosen for this development was a high-mileage 2008 Pontiac Solstice, with over 800,000 km on the odometer. Higher-mileage cars tend to have increased blowby, and blowby is one of the factors found in the literature review affecting GDI IVD. To verify mechanical integrity, the engine was disassembled, measured, and found to be in conformance with service manual specifications regarding ring end gap, cylinder bore diameter, and bearing clearance. It was then reassembled for continued test use. Throughout its life as a test vehicle, this vehicle's engine had shown a propensity to build a significant amount IVD in as few as 40,000 km using the specified service-fill oil. This vehicle had been in service as a test-car since new, and had experienced multiple valve-cleaning services during its lifetime. The engine, with a GM designation code of LNF had a displacement of 2.0 L (1998 cc) and a compression of 9.2:1. Maximum boost was 1.4 bar with a maximum output of 190 kW at 5300 rpm. The valve configuration was four per cylinder.

Test Oil

In an effort intended to accelerate the rate of IVD formation and to increase the signal-strength from the oil-related additive elements, the author used his knowledge of oil chemistry to create a specialized

baseline oil. The oil contained approximately 25% more additive elements than normal and incorporated a slate of highly-volatile base stock oil.

Table 1 lists the physical and chemical properties of the test oil, evaluated using test methods appropriate for engine lubricating oils. To give these values context, the values for Phosphorus concentration and NOACK volatility are compared to the latest minimum oil quality standard published by the American Petroleum Institute (API).¹

Table 1. Physical and Chemical Properties of Baseline Oil

Physical Property	New Test Oil	API SN Maximum
Kinematic Viscosity @ 100°C, cSt	11.14	
Kinematic Viscosity @ 40°C, cSt	65.58	
Viscosity Index	163	
Cold-Cranking Viscosity, cP	5415	
Mo, ppm	98	
P, ppm	942	800
Zn, ppm	1118	
B, ppm	278	
Mg, ppm	11	
Ca, ppm	2786	
Total Base Number, mg KOH/g	9.68	
NOACK Volatility, %	21.8	15

Test Fuel

In order to avoid potential artifacts or severity associated with the use of atypical reference fuels, a single large batch of commercial premium unleaded gasoline containing 10% ethanol was acquired from a local terminal and used throughout the test.

To provide a chemical marker to evaluate fuel dilution and blowby, a fuel-soluble manganese-based compound was splash-blended into the test fuel. Through normal combustion, this marker should find its way into the oil via blowby gas, and onto the intake valves via exhaust-gas recirculation.

Operating Cycle

The Pontiac Solstice test vehicle was operated by a robotic driver on a mileage accumulation dynamometer (MAD) according to a driving pattern previously known by the author to develop a measurable quantity of IVD in PFI vehicles. The speed versus distance profile for the cycle is shown in Figure 4. This cycle was repeated 131 times, for about 16,000 km of driving (about 10,000 miles). Each new cycle began immediately following the prior cycle, and the vehicle was only briefly shut down for fueling (about every seven cycles).

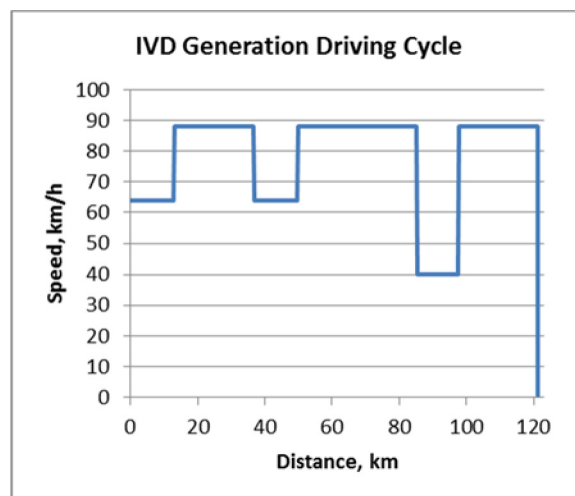


Figure 4. IVD Generation Vehicle Driving Cycle

Road Load

Appropriate road-load coefficient settings were used to simulate rolling resistance and aerodynamic drag for the 2008 Pontiac Solstice while it was operated on the chassis dynamometer. Road-load settings are empirically determined using a standard coast-down process and summarized by the United States Environmental Protection Agency (US-EPA) for most cars sold in the United States². In application, the dynamometer-control computer software adjusts the resistance of the contact roll to be consistent with vehicle speed as if it were being operated on a flat road.

Vehicle Record Keeping and Data Logging

Due to the steady-state nature of the test conditions, data from the vehicle, dynamometer, and environment were logged at fifteen-second intervals (0.67 Hz) on the test cell's data-logging computer. Standard dynamometer output variables such as speed, torque, and horsepower were logged along with the input variables. The vehicle was instrumented to enable logging of basic operational engine and vehicle variables such as engine speed, road speed, coolant, and oil temperatures. Ambient conditions were recorded from an adjacent weather station, and more advanced vehicle metrics were monitored using a link to the vehicle's OBDII computer³. Fuel consumption was determined when the vehicle's tank was refilled, approximately five times per day. Oil consumption was visually determined at end-of-test by recording the amount low on the dipstick.

Engine Rebuild

To minimize total test length and downtime, only those parts of specific interest were replaced before the start of each test. These included the fuel injectors, the intake valves, and the spark plugs. The combustion chamber surfaces on the cylinder head were cleaned of

1. The maximum allowable concentration of phosphorus is 800 ppm, which is intended to reduce catalytic converter deactivation from phosphorus poisoning. The phosphorus-containing anti-wear additive zinc dialkyldithiophosphate decomposes during normal engine operation and releases phosphorus into the oil vapors, which are consumed during combustion of the PCV gas. Phosphorus has been shown to mask precious-metal catalytic sites within the converter's wash coat. NOACK volatility is specified at 15%, maximum, to reduce oil volume loss in the crankcase. For more information on oil quality, obtain current publications of SAE J300 and API 1509.

2. See US-EPA Home, Transportation and Air Quality, On-road Vehicles and Engines, Cars and Light Trucks, Test Car List Data Files. (<https://www3.epa.gov/otaq/tcldata.htm>)

3. OBDII stands for "on-board diagnostics II," a standardized, computer-based system mandated by the US EPA and built into all model year (MY) 1996 and newer light-duty cars and trucks. OBD monitors the performance of some of the engines' major components, including emission controls. All vehicles with OBD have a standard 16-pin link, usually on the driver's side of the car, beneath the dashboard. Computerized linking tools are readily available to interrogate the OBD computer and retrieve test information.