Legacy Vehicle Fuel System Testing with Intermediate Ethanol Blends

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Golden, Colorado

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Technical Report
NREL/TP-5400-53606
March 2012

Contract No. DE-AC36-08GO28308

NATIONAL RENEWABLE ENERGY LABORATORY

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Prepared under Task Nos. FC08.0071 and VTP2.0070

The work at Kettering University was performed under NREL subcontract number ACI-0-040434-01.

NREL Technical Monitor: Matthew Ratcliff

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Acknowledgment

This project was sponsored by Dennis Smith at the U.S. Department of Energy Vehicle Technologies Program under the Clean Cities program.

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Executive Summary

The goal of this project is to make a high-level compatibility assessment of legacy vehicle fuel system components to intermediate blends of gasoline and ethanol, specifically focusing on vehicles produced in the mid-1990s. These vehicles were designed before ethanol was a common gasoline component; therefore, their tolerance to higher concentrations of ethanol is not certain.

This research project compared the effects of two blends of ethanol fuel on legacy fuel system components. An ethanol gasoline blend of 10% by volume ethanol (E10) was used for the control group, and a 17% ethanol by volume (E17) blend was used for the test group. The fuel systems tested comprised a fuel sending unit with pump, a fuel rail and integrated pressure regulator, and the fuel injectors. These systems were assembled into test rigs and operated to simulate the exposure received while driving. Specifically, the fuel pumps were cycled off and on and the fuel injectors were cycled with varying pulse widths during endurance testing. The performance characteristics of the systems and components were measured and periodic physical inspections were conducted to determine whether E17 fuel would lead to unusual degradation due to material incompatibilities. The aging testing lasted a minimum of 1,000 hours, which nominally simulates about 25,000–30,000 miles of highway vehicle travel.

Fuel system components from three common mid-1990s vintage vehicle models were studied. Parts were chosen for the following vehicle/engine families:

- 1995-6 Ford Taurus with 3.0L-V6-2V VIN U engine (without flex-fuel)
- 1993-6 General Motors 3.1L-V6-2V VIN M engine (various vehicle models)
- 1995 Toyota Camry with 3.0L-V6-4V 1MZ-FE engine

These vehicles were chosen as they represent models selling more than 100,000 units. In addition, all engines chosen were of the same configuration (V6).

Because the goal of the testing for this project was to screen for gross material incompatibilities that could lead to failure, original used components were desired. To ensure the highest likelihood of finding vintage used parts, the fuel system components were found in salvage yards. The uncertainty in this approach is that the operational history and the amount of time that the fuel system components remained out of service are also unknown. This adds a level of uncertainty to the test results. However, this study was designed to look for gross failures. Further, the performance or physical change of the components during testing is compared for the two fuel mixtures, thus minimizing the effects of the initial condition.

To simulate real world exposure, pump grade E10 was acquired from a local gasoline supplier. The E17 fuel was created by splash blending the E10 fuel with denatured, fuel-grade ethanol meeting ASTM International (ASTM) D4806 specifications. The actual concentrations of ethanol were tested and found to be 10.4 vol% and 19.5 vol%. Fuel was purchased in a single batch to eliminate variations. Excess fuel was then stored at room temperature with an inert gas cap to minimize the aging effects.

The fuel system components were initially characterized and then installed and tested in sample aging test rigs. The sample aging test rigs simulated the exposure and operation of the fuel

system components in an operating vehicle. That is, the aging rigs periodically cycled the pumps on and off. The fuel injectors were also cycled with varying pulse widths during pump operation. Operational performance, such as fuel flow and pressure, was monitored during the aging tests. The aging systems were shut down after intervals of operation and periodic tests and inspections were conducted. Periodic testing and assessment were conducted on all the relevant parts of the system. The fuel injectors, fuel pressure regulators, and fuel pumps were all tested to determine their condition. Fuel filters were also examined and replaced at each assessment interval.

A rating system was developed to semi-quantify the changes in physical measurements and observations made during the different phases of testing. The following scale was used: no change in performance/condition during testing received a zero, improved performance/condition received a positive number, and degradation in performance/condition merited a negative rating. Larger magnitudes were indicative of more severe change.

A summary of the results for the fuel pumps is presented below. Using this scale, both the Ford and General Motors fuel pumps showed little negative change during testing. Both of the Toyota fuel pumps demonstrated some degradation in performance during testing. Further, the degradation of the E17 pump was more pronounced than that of the E10 pump, potentially indicating additional problems when using E17. However, no gross failures were observed due to exposure to E17.

Summary of Fuel Pump Ratings

	Characterization: Deadhead Pressure	Characterization: Flow Rate	Endurance Performance	Visual Comparison	Fuel Related Failures	Total
Ford E10	0	1	0	0	0	1
Ford E17	0	0	-1	0	0	-1
GM E10	0	-1	0	0	0	-1
GM E17	0	0	0	0	0	0
Toyota E10	-1	-1	-1	0	0	-3
Toyota E17	-2	-2	-2	0	0	-6

A similar effort was undertaken for the fuel injectors. The following table demonstrates the results for the injectors. The injector operational history for all of the injectors is unknown; therefore, a conscious attempt was made to mix injectors from all sources in the test rigs. Six injectors were tested in each aging rig. Again, no gross failures were observed that could be attributed to exposure to E17.

The Ford and GM injectors showed little change over the aging tests. In fact, the GM injectors operated using E10 demonstrated slight increases in performance. The Toyota injectors did show some degradation in performance during the aging tests, although quantifying the results is difficult as the injectors were not linear over much of the operating range. This non-linearity complicates the typical calculations used to produce linear flow parameters such as the slope, offset, and linear flow range according to the SAE standard practice. However, since the decrease in performance is similar for both the E10 and E17 injectors, it is difficult to conclude that E17 exerted any influence on the Toyota injectors. That degradation in flow is similar for both sets, leads to the conclusion that the injectors were probably in poor condition due to their prior history.

Fuel Injector Ratings Comparison

	Character-ization: Static Flow Rate	Character-ization: Slope	Character-ization: Linear Flow Range	Character-ization: Offset	Visual Compar-ison	Fuel-Related Failures	Total
Ford E10	0	0	0	0	0	0	0
Ford E17	0	0	0	0	0	0	0
GM E10	1	0	1	1	0	0	3
GM E17	0	0	0	0	0	0	0
Toyota E10	-1	-1	-2	-2	0	0	-6
Toyota E17	-1	-1	-2	-2	0	0	-6

The unknown component history makes it difficult to precisely evaluate the results from this limited set of fuel systems. For example, all of the components tested are at least 10 years old. According to the U.S Department of Energy (U.S. Department of Energy, 2011), the average number of miles driven per year is around 12,000. This would mean that components used could already have been operated for 120,000 miles. Further, the aging test added an equivalent mileage of 25,000–30,000 miles. Therefore, the fuel pumps, rails, and regulators could potentially have an equivalent mileage of over 150,000 miles when reaching the 1,000-hour milestone. The question then becomes one of which components will fail first, the fuel system components or some other vehicle system.

Overall, based on the results of both the fuel pump testing and the fuel injector testing, no major failures were observed that could be attributed to E17 exposure. There *might* be slightly more degradation in the Toyota fuel system component performance when using E17; however, this result is not certain due to the many factors described previously. Clearly, none of the systems indicated any gross incompatibilities to the E17.

This study was intended to screen for gross incompatibilities to higher ethanol blends (E17). To determine a more precise response of these vintage components to this level of ethanol exposure, additional testing would need to be done. The unknown fuel component histories add a large uncertainty to the aging tests. Acquiring fuel system components from operational legacy vehicles would reduce the uncertainty. The vehicle odometer readings would provide valuable operational detail. In addition, the vehicles could undergo emissions and performance testing prior to testing to estimate the condition of the fuel system. Finally, none of the internal portions of the components would have been exposed to weather, etc., while stored in salvage yards. However, this approach is not without problems as there is a high likelihood that at least some of these components would already have been replaced. This means that these components would have an unknown time in service. Further, the materials and construction of aftermarket components are often changed from the original parts; thus, they may have been designed for modern E10 fuel.

Acquiring a larger sample size would also reduce the effects of unknown history and would also improve the precision of the results gathered from running vehicles.

Finally, operating the fuel system components under more severe conditions would also provide more details of the effect of E17. For example, operating at elevated temperatures might increase the chemical susceptibility of the fuel system materials.

1 Introduction

1.1 Objective

Ethanol is known to have compatibility issues with some metals and plastics. Since “gasoline” in the United States is commonly a blend of 10% ethanol and 90% gasoline by volume (known as E10), the fuel systems of new vehicles have been designed to be compatible with this blend. In a final ruling under the Clean Air Act, the U.S. Environmental Protection Agency ruled that all 2001 model year and newer light-duty motor vehicles can use gasoline with ethanol up to 15% (E15) fuel under certain conditions (U.S. Environmental Protection Agency, 2011). However, vehicles built in the 1990s were designed before ethanol was a common component of the fuel; therefore, their tolerance to higher concentrations of ethanol is not certain.

The goal of this project is to determine the compatibility of legacy vehicle fuel system components to intermediate blends of gasoline and ethanol, specifically focusing on vehicles produced in the mid-1990s. This research project compared the effects of two blends of ethanol fuel on legacy fuel system components. An ethanol gasoline blend of 10% by volume ethanol was used for the control group (E10), and a 17% ethanol by volume (E17) blend was used for the test group. The fuel system was directly tested, including the fuel sending unit consisting of a pump, fuel rail, and integrated pressure regulator, and the fuel injectors. These systems were assembled into test rigs and operated to simulate the exposure received while driving. Specifically, the fuel pumps were cycled off and on, and the fuel injectors were cycled with varying pulse widths during endurance testing. The performance characteristics of the systems and components were measured and periodic physical inspections were conducted to determine whether E17 fuel would lead to unusual degradation due to material incompatibilities. For this project, used parts were obtained from vehicle salvage yards and tested.

1.2 Background

Ethanol is an oxygenated fuel, specifically a 2-carbon alcohol with the formula C_2H_5OH (Figure 1). When ethanol is added to gasoline, the oxygen it bears reduces the amount of carbon monoxide and unburned hydrocarbons (National Science and Technology Center, 1997) in the exhaust gas. Due to this, the U.S. Environmental Protection Agency has mandated the use of oxygenated fuels in certain areas (United States of America, 1990). Studies have demonstrated that intermediate blends of ethanol produce even better emissions results. For example, one study has shown that use of E20 caused a 12% decrease in carbon monoxide emissions, while non-methane hydrocarbons decreased by 15% on average when compared with gasoline alone (Keith Knoll, personal communication, February 2009). Further, ethanol is made chiefly from domestic resources; therefore, it lowers the amount of imported petroleum required for transportation. This has led to a desire to increase the typical ethanol blend from 10% to an intermediate blend level of 15%. During 2007, the Energy Independence and Security Act mandated an increase in renewable fuel usage for the entire transport sector (U.S. Enviromental Protection Agency, 2010).

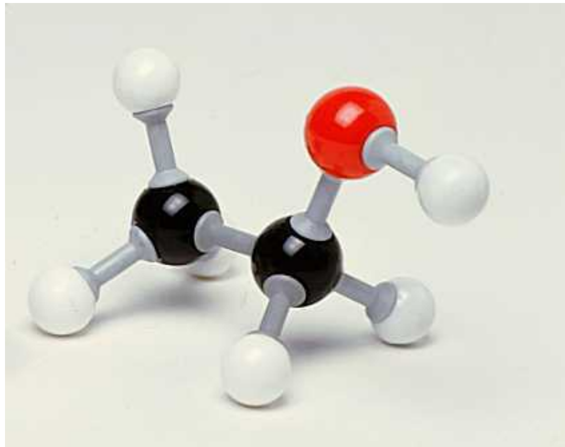


Figure 1: Ethanol molecule

Some materials (discussed in more detail below) commonly used with older gasoline-powered vehicles are not compatible with ethanol. These materials degrade when in contact with ethanol, which may lead to leaks or fuel system contamination (U.S. Department of Energy, 2005). Fortunately, there are many alternatives for these incompatible materials, which have been replaced in modern vehicles. Unfortunately, the timing of the material substitutions varied from manufacturer to manufacturer and as new models were introduced; therefore, it is difficult to know which models and vehicle years are incompatible without extensive testing. Ethanol material compatibility is discussed below for metallic and non-metallic compounds.

1.2.1 Metallic Substances

Metallic substances that are degraded by ethanol include zinc, brass, aluminum, and lead-plated steel. These materials can react with ethanol, partially dissolving in the fuel. This can contaminate the fuel system, leading to clogged fuel filters and injectors, which in turn cause poor vehicle drivability. Unfortunately, many vehicles use aluminum in the fuel delivery systems to save weight, including in the fuel pump, lines, fuel rail, and fuel pressure regulator. Furthermore, older vehicles often use lead-plated steel for the vehicle fuel storage tanks. However, most modern vehicles use fuel storage tanks that are made of ethanol-resistant polymer compounds. Aluminum can be safely used if it is hard anodized or nickel-plated.

Other metallic compounds that are resistant to ethanol include unplated steel, stainless steel, black iron, and bronze.

1.2.2 Nonmetallic Substances

Nonmetallic materials that degrade when in contact with ethanol include natural rubber, polyurethane, cork gasket material, leather, polyvinyl chloride (PVC), polyamides, methyl-methacrylate plastics, and certain thermo and thermoset plastics.

Older vehicles may still use rubber, polyurethane or cork gaskets and O-rings for sealing fuel delivery systems; fortunately, most late model vehicles (vehicles produced after the mid-1990s) no longer use these materials in favor of more advanced sealants.

Nonmetallic materials that are resistant to ethanol degradation include nonmetallic thermoset reinforced fiberglass, thermoplastic piping, thermoset reinforced fiberglass tanks, Buna-N, neoprene rubber, polypropylene, nitrile, Viton, and Teflon. The ethanol tolerance of these materials varies with grade or compound as well as the ethanol content of the fuel. Modern vehicles use ethanol-tolerant materials for gaskets and O-rings; for example, most automakers now use Viton O-rings to seal their fuel injectors.

1.3 Scope of Work

Fuel system components from three common mid-1990s vintage vehicle models were studied. Two sets of components from each model were used, one for the control group and one for the test group. The control group was tested with E10 fuel and the test group was operated with E17 fuel, which was used here to represent a stronger blend of E15 that may be commercially distributed in some cases. The fuel systems to be tested were taken from automotive salvage yards. Parts were chosen for the following vehicle/engine families:

- 1995–6 Ford Taurus with 3.0L-V6-2V VIN U engine (without flex-fuel)
- 1993–6 General Motors 3.1L-V6-2V VIN M engine (various vehicle models)
- 1995 Toyota Camry with 3.0L-V6-4V 1MZ-FE engine

These vehicles were chosen as they represent models selling more than 100,000 units. In addition, all engines chosen were of the same configuration (V6).

The fuel system components tested are:

- Fuel sending unit with pump
- Fuel injectors
- Fuel injector rail with pressure regulator

The goal of the testing for this project was to screen for gross material incompatibilities that could lead to failure. Therefore, used components that were truly from mid-1990s vehicles were desired. To ensure the highest likelihood of finding vintage used parts, the fuel system components were found in salvage yards. The uncertainty of this approach is that the operational history is unknown. In addition, the amount of time that the fuel system components remained out of service is also unknown, adding a level of uncertainty to the test results. However, some of this uncertainty is minimized when the performance or physical change or degradation during testing is compared for the two fuel mixtures. That is, the absolute values are not as relevant as the change over the duration of the aging tests. Still, a component that was exposed to an extensive period of disuse with the internal components exposed to the environment may fail due to that reason alone.

Acquiring parts from running vehicles might alleviate some of this uncertainty; however, this approach is not without problems as there is a high likelihood that at least some of these components would already have been replaced. This means that these components would still have an unknown time in service. Further, the materials and construction of aftermarket components are often changed from the original parts; thus they may have been designed for use with ethanol-blended fuels. Finally, the cost of this approach was deemed to be beyond the scope of this project.

Pump grade E10 was acquired from a local gasoline supplier. The E17 fuel was created by splash blending the E10 fuel with denatured, fuel-grade ethanol meeting ASTM International (ASTM) D4806 specifications. To ensure proper blending, the exact ethanol contents were determined by Southwest Research Institute for analysis by ASTM Methods D5501 or D5599 as appropriate. The fuel-grade ethanol used for blending E17 was 93.0 vol%, and the test fuels' ethanol contents were 10.4 vol% and 19.5 vol % for E10 and E17, respectively. In addition, fuel ethanol content was verified using a GM/Siemens flex-fuel sensor, which is calibrated to within ±0.1 percent. Fuel was purchased in a single batch to eliminate variations. Excess fuel was then stored at room temperature with an inert gas cap to minimize the aging effects.

The fuel system components were initially characterized and then installed and tested in sample aging test rigs. The sample aging test rigs simulated the exposure and operation of the fuel system components in an operating vehicle. That is, the aging rigs periodically cycled the pumps on and off. The fuel injectors were also cycled with varying pulse widths during pump operation. Operational performance, such as fuel flow and pressure, was monitored during the aging tests. The aging systems were shut down after intervals of operation, and periodic tests and inspections were conducted. The aging systems were then placed back into service for additional aging. Changes in performance and physical characteristics were noted throughout the duration of the tests. Fuel samples taken during intervals throughout testing were sent to an external laboratory for analysis. The aging testing lasted a minimum of 1,000 hours, which nominally simulates about 25,000–30,000 miles of highway vehicle travel.

2 Development of the Experimental Test Units

A total of six experimental test rigs were constructed. Three were used as the control group and three as the test group. Each group contained Ford, GM, and Toyota fuel system components. The experimental test rigs had to meet four major requirements: each apparatus had to physically house the fuel system test components; the rigs had to accommodate the data acquisition system, which was required to monitor and record all the performance data during testing; each rig had to control the fuel pumps and injectors to simulate in-vehicle operation; and finally, the rigs could not contribute to any possible material incompatibilities.

A photograph of the completed units, located in the fuel-testing laboratory is shown in Figure 2.

Figure 2: Photograph of the six endurance testing units developed for the project

2.1 Unit Design Overview

The test rigs were designed to house and operate the fuel system components. The rigs are essentially models of vehicle fuel systems without the engine. A data acquisition rail was designed and inserted between the fuel sending unit and the fuel injection rail to measure relevant fuel data during operation. Each test rig consists of the following components:

1. Fuel Tank
2. Fuel Sending Unit
3. Fuel Supply Line
4. Data Acquisition Rail
    a. Thermocouple

b. Pressure Transducer
c. Flow Rate Meter
d. Valve
5. Fuel Rail
a. Fuel Pressure Regulator
6. Fuel Injectors
7. Fuel Return Lines

A functional representation of the experimental setup design is shown in Figure 3. A photograph of the finished product is shown in Figure 4 with the visible components labeled. The fuel tank (1) is a five-gallon stainless steel unit with a removable lid to allow access for periodic fuel sampling. The lid had openings cut into it to accommodate the fuel sending unit (2) and the fuel returning to the tank from the fuel injectors (6). Openings were made to accommodate the argon safety cap fitting and the pressure relief valve. The fuel sending unit (2) housed the fuel pump, fuel level gauge (not used), pre-filter, and the supply and return hard-line lines. The fuel sending unit was not changed except that the inlet and outlet tubes were modified as needed to allow for the supply and return line attachment (Figure 5). The fuel supply line (3) connected the fuel sending unit to the data acquisition rail and then to the fuel rail. A fuel filter was inserted in the supply line between the sending unit and the data acquisition rail.

The data acquisition rail (4) was made from 304 stainless steel piping and had inserts for the thermocouple, pressure transducer, flow rate meter, and a shut-off valve. The data acquisition design is covered in more depth in Section 2.2. The data acquisition rail was then connected by supply line to the fuel rail (5) and integrated pressure regulator (5a). The end fittings of the fuel rail were slightly modified to allow for the supply and return lines to be attached. The fuel rail houses the fuel injectors (6). A plate was designed to hold the injectors onto the rail (Figure 6). Tygon PVC tubing was used to connect the outlets of the fuel injectors to the tank. This allowed visual confirmation of the flow from the injectors during operation. The fuel return line (7) connects the rail outlet to the tank, completing the fuel flow circuit.

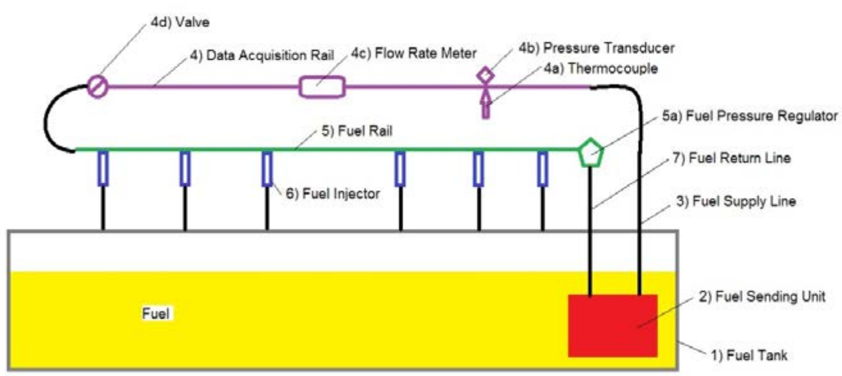


Figure 3: Schematic of the experimental test rigs

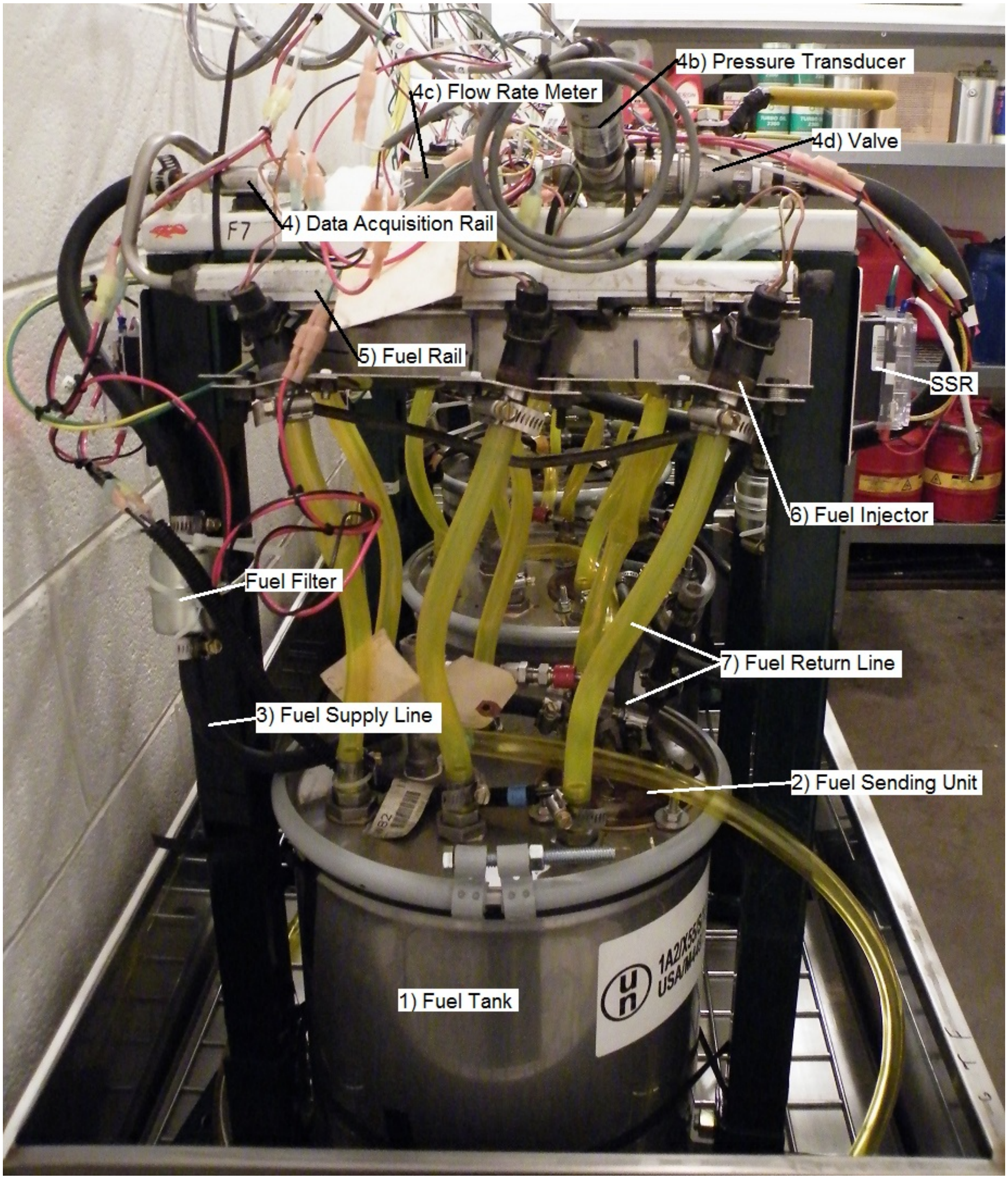


Figure 4: Experimental units

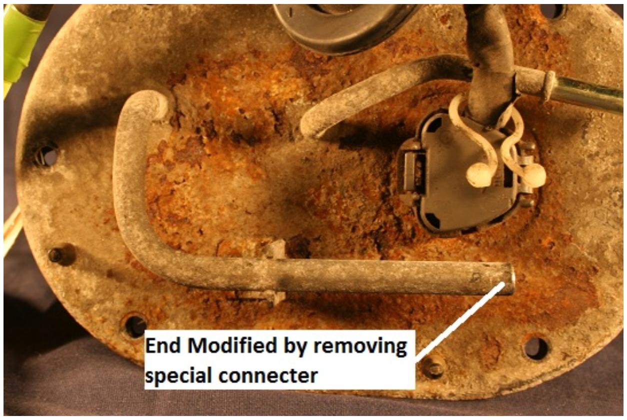


Figure 5: Modified fuel sending unit end

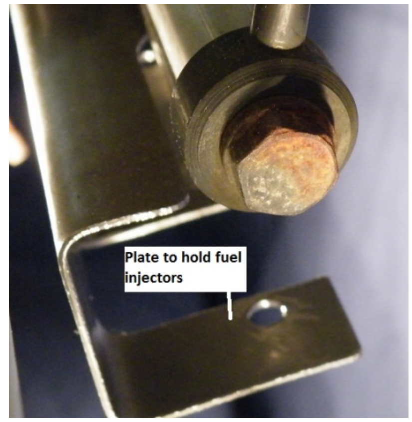


Figure 6: Plate to hold fuel injectors in place

To minimize the possibility of contaminating the fuel system components being tested, everything but the components being tested was selected from materials that are compatible with both gasoline and ethanol.

The fuel tank, fittings, and data acquisition rail were made of 304 stainless steel. The lid and all openings were sealed with expanded polytetrafluoroethylene (PTFE). The fuel supply and return lines were fabricated using high pressure flex-fuel line from Goodyear (part # 65151, 65152, and 65153 depending on size needed), which uses a nitrile liner and meets SAE International (SAE) standard J30R9, a standard for hose material used in fuel delivery systems. Low-pressure lines leading from the fuel injector nozzles to the tank were made of fuel- and lubricant-safe yellow Tygon PVC tubing to allow visual confirmation of injector fuel flow during operation. To prevent mechanical damage from foreign debris, a standard fuel filter was used with each unit. The filter was a standard aftermarket replacement filter (Carquest Auto Parts Part #R86032).

2.2 Data Acquisition and Control System Development

Two data acquisition and control systems were used to conduct the tests, one for the E10-fueled systems, and one for the E17 test systems. The systems selected were CompactRIO (cRIO) reconfigurable embedded control and acquisition system from National Instruments. Each system operated one of three tests rigs in sequence: one Chevrolet, one Ford, and one Toyota. cRIO A was used to control and gather data from the E10 systems, and cRIO B controlled and gathered data from the E17 systems. This layout allowed for the simultaneous operation of two test rigs. The cRIO systems were also used to acquire and record operational data from each fuel system during operation. Details of these test systems are provided in the following sections.

2.2.1 cRIO Hardware Selection

Each cRIO unit consists of an embedded chassis (part number 9114) that can hold four data acquisition/control modules. A photograph of one of the cRIO units is shown in Figure 7. Slot 1 holds a digital input/output (DIO) module used to energize the fuel pumps and injectors (NI 9401, DIO 5V TTL). Slot 2 holds an analog input module used to measure pressures and system voltage (NI 9221, Analog +/- 60V). Slot 3 holds a digital input (DI) module that was used to measure fuel flow rates (NI 9423, DI 24V Sink, Counter Mode). Slot 4 holds a thermocouple input module used to measure the fuel and ambient temperatures and the current shunt voltages (NI 9213, TC, Type J Mode).

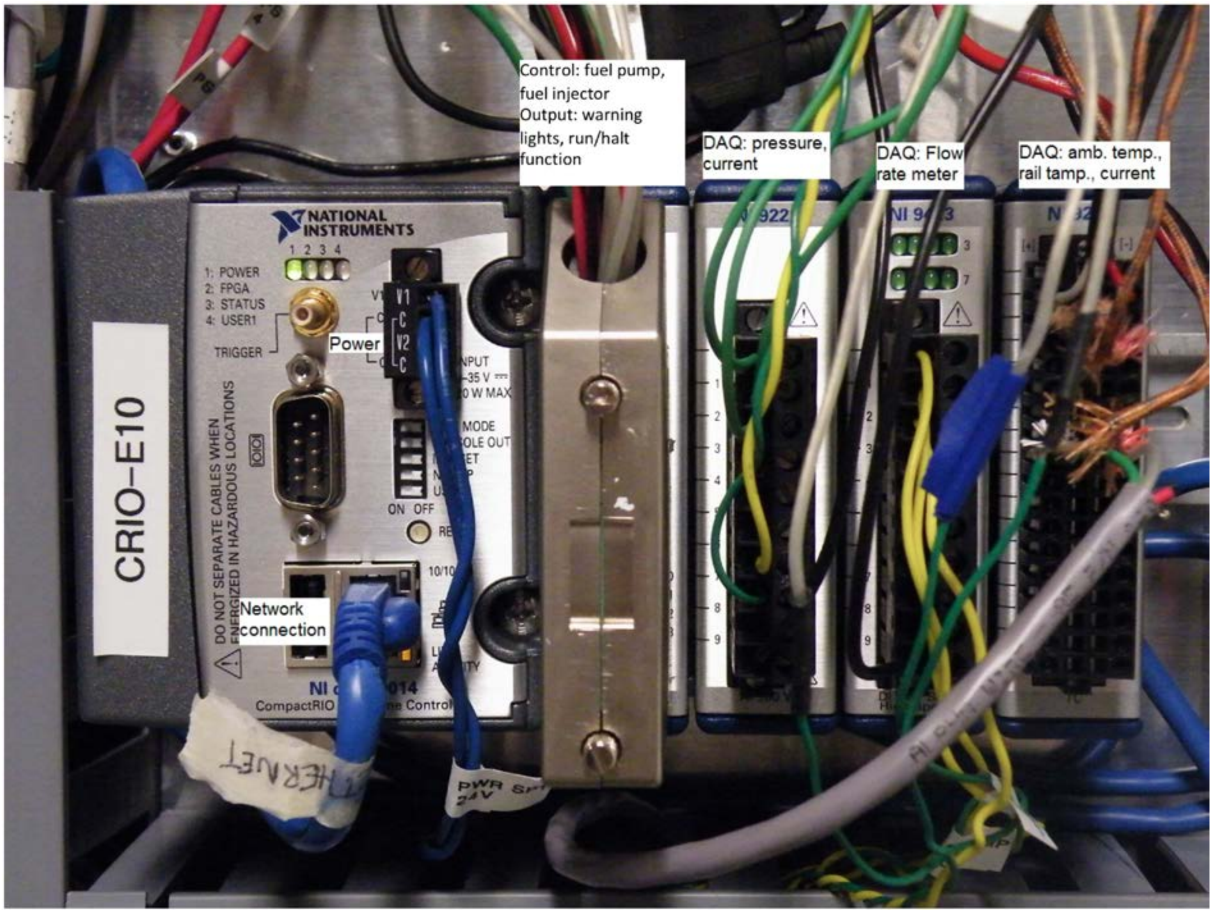


Figure 7: cRIO data acquisition and control system

2.2.2 Test Unit Control System

To reduce costs, one high current, 12 VDC power supply (Pyramid Model PS-21KX) was used for each cRIO system to power both the fuel pump and the fuel injectors. The fuel injectors for each unit were not controlled sequentially, but were fired simultaneously. The fuel pump and fuel injectors for each system were controlled using solid state relays. Two solid-state relays (SSRs) were used for each system (Omega Engineering Model Number SSRDC100VDC20), one for the fuel pump, and the other for the fuel injectors (batch fire the injectors). This is depicted in Figure 8. A second, smaller power supply was used to power the cRIO units and the transducers (National Instruments NI PS-15). A more detailed power schematic is shown in Figure 9.

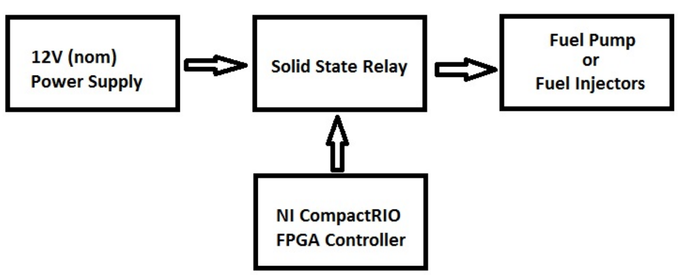


Figure 8: Power control system

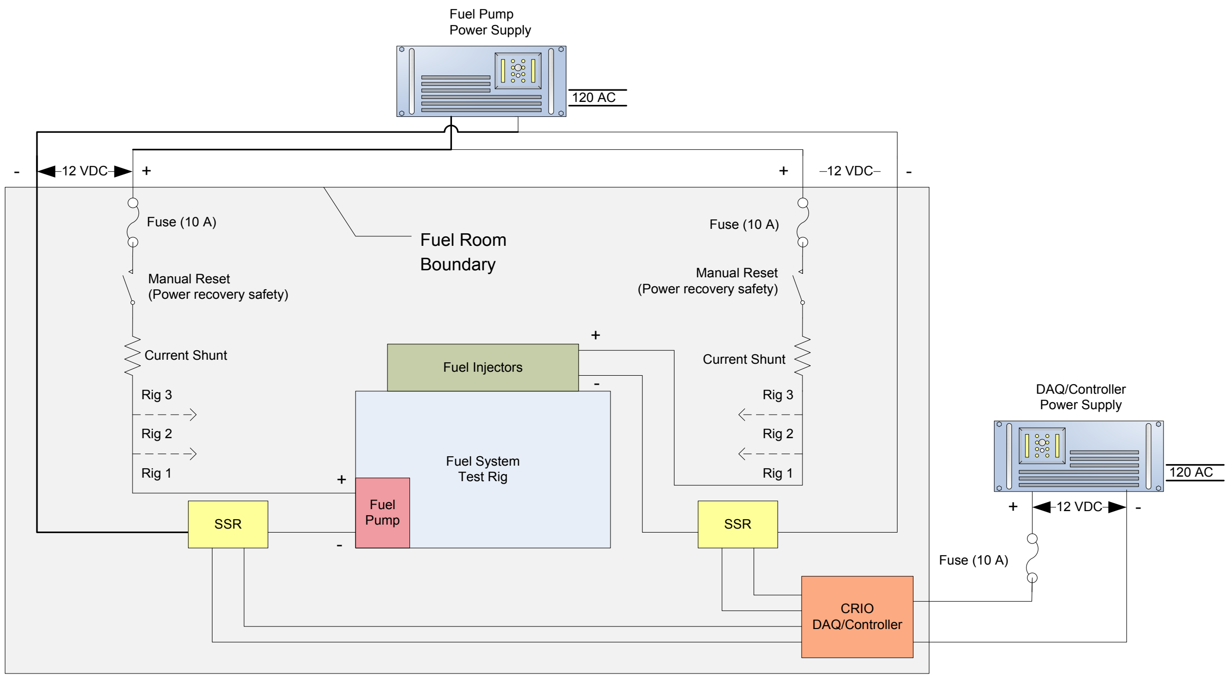


Figure 9: Aging test rig control system schematic

For safety, the high voltage components were housed in a control cabinet, which was located outside of the fuel test laboratory. Only 12 VDC power was routed into the laboratory itself. Further, the only switching operations conducted in the laboratory utilized SSRs. This minimized the chance of sparking. A photograph of the control cabinet is shown in Figure 10.

The programming for the controller was done in National Instruments LabVIEW Real Time. The cycle used in controlling the units is covered in Section 3.1. The fuel sending unit and fuel injector power was cycled on and off by outputting a power signal to the SSRs.

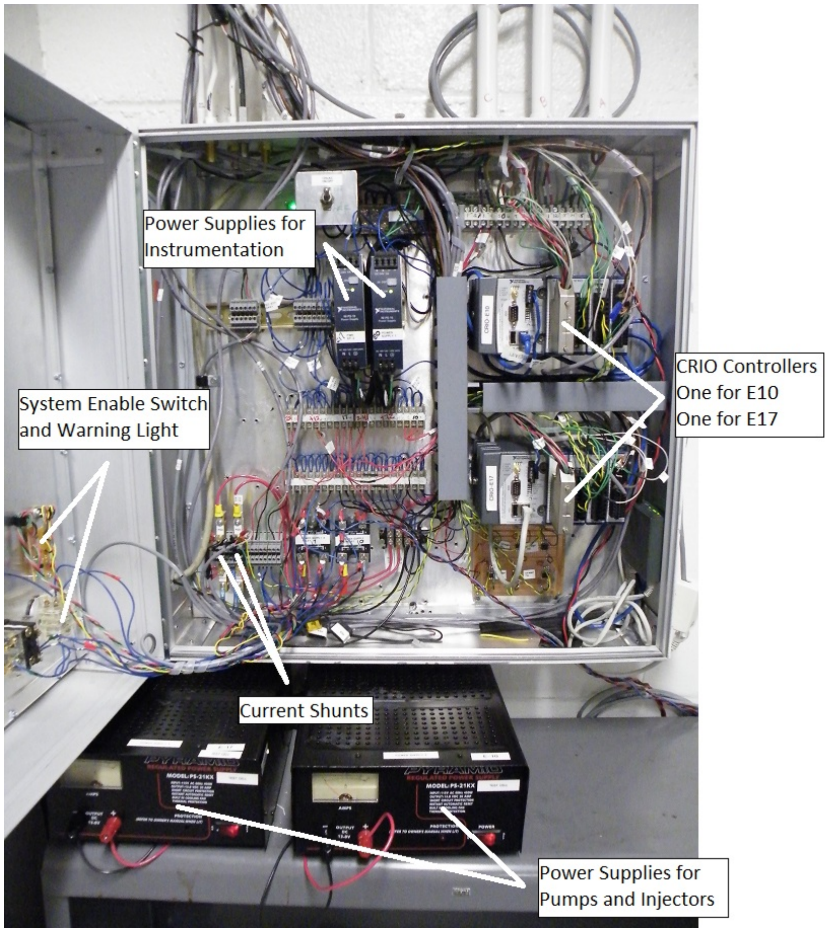


Figure 10: Control panel box

2.2.3 Selection and Calibration of Data Acquisition Equipment

The data acquisition system monitored and recorded data during the endurance testing. The following data was collected and recorded during system operation:

- Pump output pressure
- Pump flow rate
- Fuel temperature in the DAQ rail
- Ambient temperature (measured about 7 ft. off from the ground)
- Power shunt voltage (indirect measurement of the pump current draw)
- Pump switch state (On/Off)
- Injector state (On/Off) and pulse width settings
- Date and time
- Manually added comments

These parameters were used to determine the change in fuel system component performance over time. The parameters were also used to determine if the units were running properly. The system was designed to automatically shut down if a problem, such as high or low pressure, was detected.

The fuel rate, temperature, and pressure sensors/transducers were housed in a data acquisition rail, which is located just upstream of the fuel injector rail. The flow rate was measured using commercial turbine flow meters (Floscan Instrument Co. Ins. model number 201, serial numbers 179901 through 179905, and 179907). All flow meters were new and came with factory calibrations; the calibrations were then verified using mineral spirits, a graduated burette, and a stopwatch. The fuel temperature was measured using a J-type thermocouple (Omega Engineering JMTSS-125U-6), calibrated using a standard mercury thermometer. A variety of pressure transducers were used to determine fuel pressure for each unit (see Table 1), and all were calibrated using a GE Druck DPI 306 pressure calibrator (Serial number 6031506008).

Table 1: Pressure Transducer Information

Unit	Ford 10%	Ford 17%	GM 10%	GM 17%	Toyota 10%	Toyota 17%
Producer	Omega	Omega	IMO	IMO	Omega	Omega
Model	PX94-100G5V	PX94-100G5V	403H2-04CG-09-0	403H2-04CG-09-1	PX213-100G5V	PX94-100G5V
Serial #	908014002	907010069	1	2	E126726	1030001
Range	0-100 psig	0-100 psig	0-100 psig	0-100 psig	0-100 psig	0-100 psig
Output	1-6 V	1-6 V	0.5-5.5 V	0.5-5.5 V	0.5-5.5 V	1-6 V
Supply	10-30 Vdc	10-30 Vdc	12-32 Vdc	12-32 Vdc	7-35 Vdc	10-30 Vdc

A J-type thermocouple was used to measure the ambient temperature in the testing laboratory. Finally, current shunts were used to measure the current supplied to the fuel sending units.

3 Fuel System Component Testing

Two types of fuel system component testing were done: endurance testing, and periodic testing. During endurance testing, the fuel system components were operated in a manner that simulated "normal" use in a vehicle. That is, the fuel pumps were cycled on and off for periods of time. While the fuel pumps were operating, the fuel injectors were also cycled with varied pulse widths to simulate different engine load conditions. Operational data were recorded during this testing using the cRIO systems. Each unit contained the same volume of fuel to minimize any accelerated degradation due to buildup of dissolved materials.

Periodic testing was conducted prior to system startup and after determined intervals of endurance testing. Periodic testing consisted of tests to characterize the fuel injectors and pumps, fuel sampling and analysis, and physical inspection of the components.

Before testing, the fuel system components were cleaned using mineral spirits (Stoddard solvent). They were then operated using mineral spirits to loosen seals and remove any remaining debris. Extra components (required in the event of failure) were then stored in plastic bags to maintain a wetted condition.

3.1 Endurance Testing

During this testing, the three test units were operated to simulate vehicle use. Each unit was operated over the same cycle. A cycle would consist of a portion of time in which the fuel pump was energized and the fuel injectors were cycled, followed by a period of rest, then a repeated fueling cycle using a different injector pulse width. Specifically, the fuel pumps were cycled on for approximately 30 minutes. During this time, the injectors were operated at a fixed pulse width. The test rig was then turned off for 60 minutes while the other two units were operated. This meant that the units were operated over a 33% duty cycle (30 minutes on/60 minutes off). Each time a unit cycled on, a different injector pulse width (PW) was used. The pulse widths rotated through 2 milliseconds, 5 milliseconds, and 8 milliseconds. The cycle period of the injectors was fixed at 10 milliseconds. These values were chosen as they correspond closely to those used in SAE Standard J1832, the test definition for low pressure fuel injectors. Further, this period correlates to an engine speed of approximately 3,000 rpm. The different injector pulse widths simulate different engine load conditions. The fuel injectors were cycled on and off during the same time period, but the pulse widths changed during each cycle; therefore, the total time required to complete an injector pulse width set was 270 minutes (3 pulse width increments × 90 minutes).

If a vehicle is travelling on the highway at the test engine speed of 3,000 rpm, it will be traveling a distance of 25,000–30,000 miles for every 1,000 hours of testing. Therefore, the fuel pump, rail, and regulator all experienced significant additional simulated mileage accumulation during testing.

The sequence of events is described below:

1. Ford unit (30 minutes)
    a. Pump on for 3 minutes

b. Injectors on 2 ms PW, for 22.5 minutes
c. Pump remains on for 3 minutes
d. Everything is off for 1.5 minutes

2. GM unit (30 minutes)
    a. Pump on for 3 minutes
    b. Injectors on 2 ms PW, for 22.5 minutes
    c. Pump remains on for 3 minutes
    d. Everything is off for 1.5 minutes
3. Toyota Unit (30 minutes)
    a. Pump on for 3 minutes
    b. Injectors on 2 ms PW, for 22.5 minutes
    c. Pump remains on for 3 minutes
    d. Everything is off for 1.5 minutes

Repeat with new pulse width…

4. Ford unit (30 minutes)
    a. Pump on for 3 minutes
    b. Injectors on 5 ms PW, for 22.5 minutes
    c. Pump remains on for 3 minutes
    d. Everything is off for 1.5 minutes

    …

The data acquisition system monitored and recorded all data during testing. This was done about every 1.5 minutes while the given test rig was operating. The data were also available in real time to indicate any problems during testing.

3.2 Periodic Testing and Assessment

Periodic testing and assessment were conducted on all the relevant parts of the system. The fuel injectors, fuel pressure regulator, and fuel pumps were all tested to determine their condition. Fuel filters were also examined and replaced. Fuel samples were taken and then sent to Southwest Research Institute for analysis. Assessments were conducted approximately every two weeks. Table 2 summarizes the number of accumulated hours and data points for each test rig. On each of the dates shown in the table, the test rigs were stopped so that fuel samples could be taken, the fuel injectors tested, and the fuel pumps tested for maximum flow rate and deadhead (no flow) pressure.

Table 2: Summary of Testing

	Ford E10		GM E10		Toyota E10			
	Hours	**Points**	**Hours**	**Points**	**Hours**	**Points**	**ΔHours**	**Comment**
02/22/11	178	2,395	178	2,395	176	2,374	176	Injector Test
03/15/11	399	5,378	398	5,366	396	5,337	221	Injector Test
03/24/11	569	7,666	567	7,646	565	7,617	169	No Injector Test
03/31/11	731	9,862	729	9,836	725	9,780	161	No Injector Test
04/04/11	815	10,984	814	10,971	812	10,941	86	Injector Test
06/30/11	---	---	1,669	22,504	1,668	22,434	857	Injector Test

	Ford E17		GM E17		Toyota E17			
	Hours	**Points**	**Hours**	**Points**	**Hours**	**Points**	**ΔHours**	**Comment**
04/15/11	162	2,204	164	2,205	158	2,135	158	Injector Test
05/06/11	371	5,055	375	5,055	369	4,973	211	Injector Test
05/25/11	701	9,559	709	9,557	703	9,475	334	Injector Test
06/03/11	842	11,479	851	11,476	845	11,394	142	Injector Test
07/07/11	1,101	15,014	1,113	14,936	1,104	14,902	260	Injector Test

Each of the E10 systems was tested for 1,600 hours (nominal) at a duty cycle of 33% (30 minutes every 90-minute period). Most of the fuel pumps, injectors, and pressure regulators continued to operate relatively “normally” throughout the duration of the test. The one exception was the Ford E10 pump, which failed at 815 hr. It was determined that the pump failure was due to a badly worn motor commutator and was unrelated to the presence of ethanol in the fuel(this will be explained in greater detail in Section 4.1.1). The E17 systems were tested for 1,100 hours (nominal). During this phase of testing, all of the fuel pumps, injectors, and pressure regulators continued to operate relatively “normally” throughout the duration of the test.

3.2.1 Fuel Injector Characterization

Each fuel injector was characterized in accordance with SAE standard J1832, “Low Pressure Gasoline Fuel Injector.” For a detailed test procedure, please see Appendix C. Each injector was characterized before the experiment began, at set time intervals during the experiment (when the units were shut down for sampling), and at the end. For each injector, data were recorded and then used to calculate four performance statistics: static flow rate, slope, flow offset, and the linear flow range (LFR).

To illustrate the physical meaning of these parameters, a typical injector performance curve, which has been redrawn from SAE J1832, is presented in Figure 11.

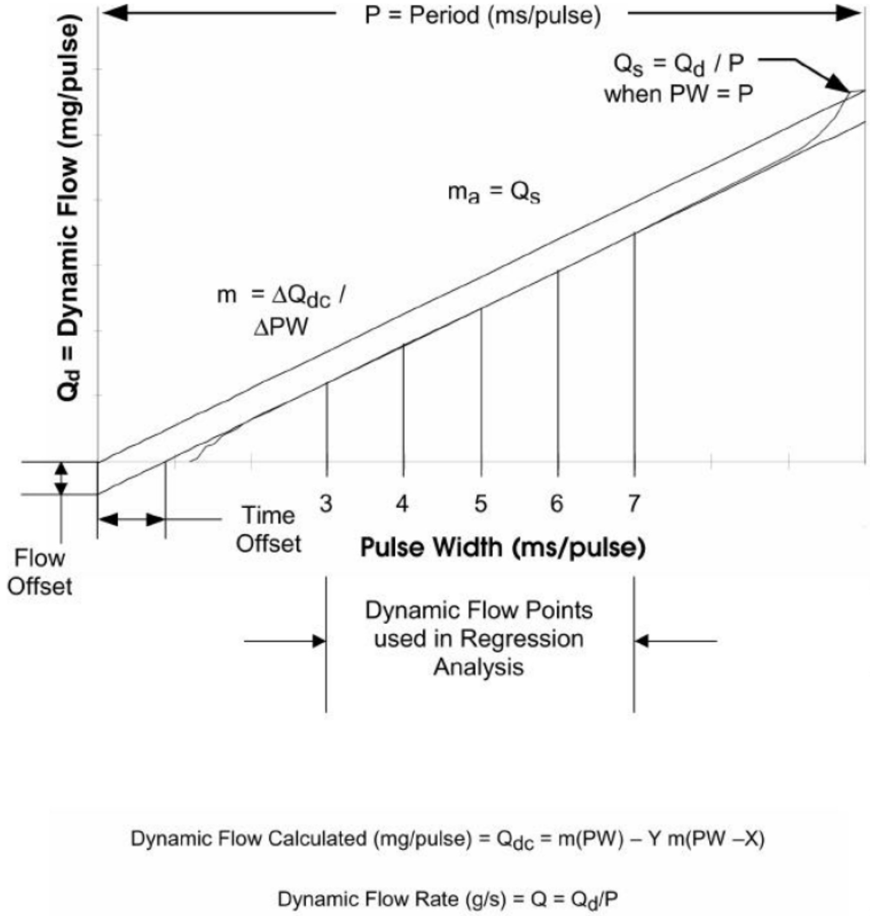


Figure 11: Characteristic injector flow curve (SAE International, 2001).

Static flow rate, Q_s, is the flow rate through the injector when it is held fully open. This is the mass of fuel delivered per unit time. This provides a rough estimation of the injector flow coefficient, or slope. Static flow rates can provide an indication of the condition of the injector flow openings. For example, if the injector openings are becoming clogged, the static flow rate will decline.

The slope, m, is the slope of the linear regression of the fuel delivered per pulse width, mg/ms-pulse, performed over the linear range of the injector. This parameter is commonly referred to as the flow coefficient of the injector. It is a measure of the actual mass flow rate of fuel delivered by the injector. It provides an indication of the size and condition of the injector openings; larger slope implies a larger flow area and/or cleaner openings. The slope and the static flow rates should be similar in magnitude; thus the static flow rate is often considered a good data validity check on the slope calculation.

The injector flow offset, mg, provides an indication of the injector mechanical and magnetic response to the commanded signal. The offset is related to the non-linear flow occurring during injector opening or closing. It is also tied to the physical response of the injector upon electrical energizing or de-energizing. A larger magnitude offset implies a slower response, which could be due to corrosion or degradation of the O-rings or pintle.

The LFR parameter is used to compare the linear flow range of injectors. The LFR is the ratio of the maximum to minimum flow rates of the injector, which are defined by comparing the measured data to values produced using a linear regression. The maximum and minimum flow rates are established by comparing the actual fuel delivered per pulse at a given pulse width, Q_d, to the value calculated by utilizing the slope and offset parameters. This is shown in the equations of Figure 11. Injector flows will deviate from the linear regression for small or large injector pulse widths due to the non-linearity associated with injector opening and closing. When this deviation exceeds 5%, the flow is considered non-linear.

LFR is sensitive to injector degradation and will respond more quickly to changes than the other parameters. For example, if an injector becomes sluggish after aging, it can still deliver most of the fuel, yielding an acceptable flow rate, but the LFR will typically degrade. Unfortunately, LFR is also sensitive to the magnitude of the dynamic flow at small pulse widths. For example, suppose the maximum flow delivered by an injector is 10 mg/pulse and the minimum delivered is 1 mg/pulse. This would provide a LFR of 10. Now suppose the minimum fuel delivered per pulse is 0.75 mg/pulse and the maximum flow value remains unchanged; the LFR is now over 13. To increase the precision of this value, SAE J1832 recommends varying the test pulse widths by 0.1 ms; unfortunately, this greatly increases the amount of data required and is impractical with a manual flow test bench; therefore, the LFR method used in this analysis yields a less precise value than recommended by the standard. This was done to minimize injector down time during the periodic tests. Although the number is somewhat coarse, it still can provide meaningful information indicative of a change in operating characteristics. LFR is directly related to the injector offset. Large offsets and LFRs imply more injector non-linearity.

Figure 12 shows the injector an injector test bench. Mineral spirits (Stoddard solvent) were used for flow testing as per the standard. A separate, dedicated fuel pump was utilized to test all the injectors. This was done to eliminate any problems that might arise in using the existing pump. Pressure was controlled by the fuel rail pressure regulator of each system. This did introduce some minor pressure fluctuations due to the condition of these old regulators. A radiator was also used to maintain a stable fluid temperature. After the fluid flowed through the radiator, it would then enter the fuel rail of the unit being tested at that time. The injectors were powered using the same DC power source from the endurance testing for flow characterization. This was done to minimize any effects due to minute changes in voltage levels. The fuel injectors were controlled using the cRIO system, by utilizing a software program that was designed for testing injectors. Fluid exiting the injectors was transported from the nozzle of the injector to burettes via tubing. The fluid was then measured in the labeled burettes and drained back into the fuel tank when finished or when zeroing out the burettes. For a detailed test procedure, please see Appendix C.

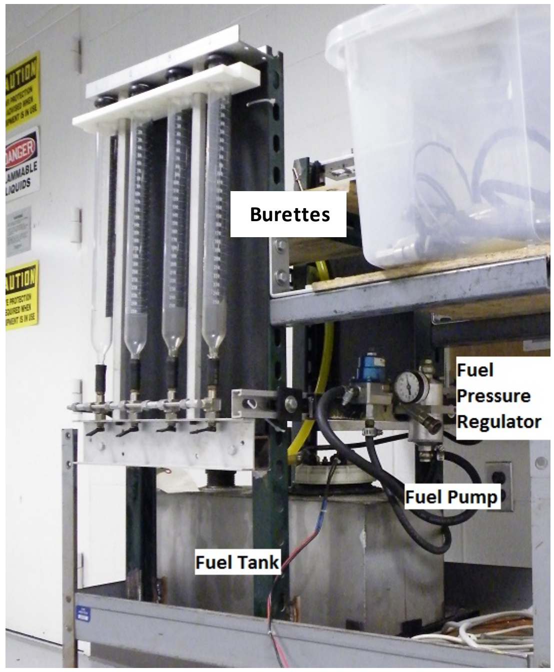


Figure 12: Fuel injector test bench

3.2.2 Pump Characterization

Like the injectors, the fuel pumps were tested and characterized before the experiment began, at set time intervals during the experiment (when the units were shut down for sampling), and at the end of endurance testing. The flow rate and rail operating pressure of each pump (without injectors operating) were recorded. In addition, the deadhead pressure (no flow) was measured and recorded for each pump by closing the valve on the data acquisition rail. Manufacturer specifications for minimum flow at both high and low pressure and deadhead pressure ranges are shown in Table 3 for new fuel pumps.

Table 3: Manufacturer Specifications for the Pumps (TI Automotive)

Manufacturer	Minimum Flow Rate at Max. Pressure (L/min)	Minimum Flow Rate at Min. Pressure (L/min)	Deadhead Pressure (psig)
Ford	1.64 @ 47 psi	1.77 @ 40.5 psi	78 – 120
GM	1.45 @ 45 psi	1.64 @ 30 psi	65 -105
Toyota	1.39 @ 38 psi	1.58 @ 33 psi	65 -109

3.2.3 Fuel Filter Inspections

Fuel filters were used to protect the system components from particles that might end up in the fuel due to degradation of any of the components. Filters were replaced after each interval when the units were shut down for fuel injector and pump characterization. Used filters were then inspected and photographed, looking for any foreign debris or discoloration of the filter media.

3.2.4 Visual Inspections

A visual inspection was made as part of the periodic inspections. Photographs were taken at the beginning and end of the aging tests. Photographs were taken to allow detailed comparisons and to observe if any changes occurred during testing. Worn surfaces and residue buildup were the key focus areas of the comparison. Only representative photographs are shown in the results (Sections 4.1.4, 4.2.4, and 4.3.4). All initial and final photographs are provided in the attached electronic supplement.

4 Results

The results of the aging testing are categorized by manufacturer. This section covers any failures that occurred and the results of the endurance and periodic testing and assessments.

4.1 Ford Results

4.1.1 Failures

No failure occurred during testing for either of the two ethanol blends during the first 800 hours of testing. Upon starting for further testing, the control (E10) fuel pump (after 815 hours) did not work. It was disassembled for inspection (Figure 13). The cause of failure was determined to be electrical. As can be seen in Figure 14, the commutator was severely worn. Also, little to no wear was shown on the gerotor of the pump, as shown in Figure 15 and Figure 16. The results of inspections indicated that the failure of the pump was not related to the presence of the ethanol in the fuel, but due to age and unknown prior history.

Figure 13: Ford E10 fuel pump inspection

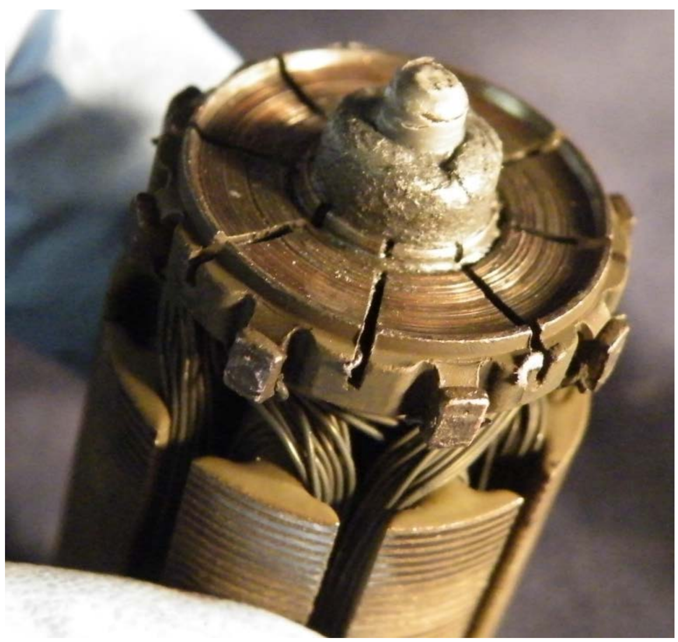


Figure 14: Commutator wear

Figure 15: Gerotor housing

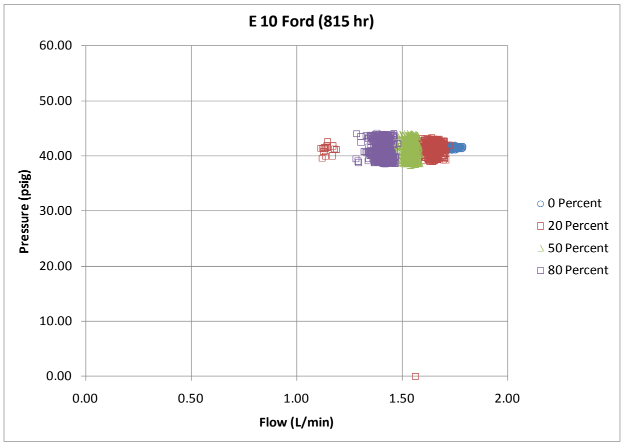
Figure 16: Gerotor

4.1.2 Endurance Testing Performance Analysis

Performance data collected by the automated data acquisition system during the endurance testing provide direct analysis of the fuel system performance during operation.

Figure 17 and Figure 18 show the operating points (pressure and flow) for the Ford fuel pumps during endurance system testing for the E10 and E17 fuels, respectively. The data points are grouped by the fuel injector duty cycle (0 percent, 20 percent, 50 percent, and 80 percent) used for the test point. The E17 fuel pump was definitely the poorer of the two pumps from the start; this is assumed to be related to its previous (unknown) usage history and is discussed further in Section 4.1.3.2. The output pressures (controlled by the pressure regulator) for the two pumps were similar, but the flow rate for the E17 pumps was nominally one-half of the flow rate for the E10 fuel pump. Both fuel pumps were able to provide 40 psi (nominal) throughout the testing at all duty cycles with the exception of the E17 pump at 80 percent duty cycle.

The operating points for the E10 units remained very consistent throughout the testing, as indicated by the tight grouping of the data points in Figure 17 and Figure 18. The operating points for the E17 showed much more variation, particularly in the flow that the pump was able to deliver. Unfortunately, the spare pump had a mechanical problem and was deemed unreliable; therefore, it was not used in testing.



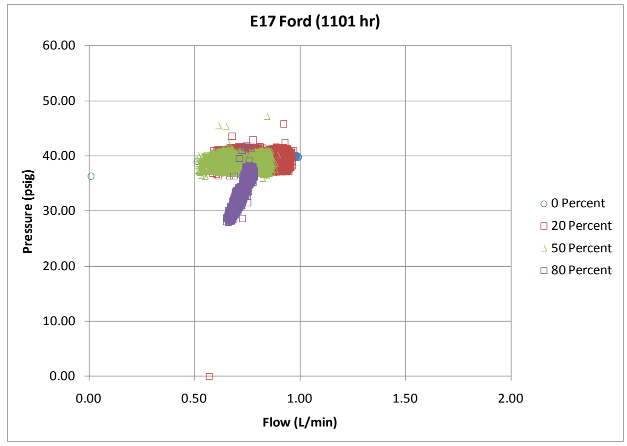


Figure 17: Ford fuel pump operating points during system testing on E10

Figure 18: Ford fuel pump operating points during system testing on E17

Figure 19 and Figure 20 show the Ford fuel pump operating characteristics as they vary over time for the E10 and E17 fuels, respectively. It should be noted that the values for flow rate (in red) should be read from the right-hand axis and the values for all other parameters are read off the left-hand axis. The data shown are for a fuel injector duty cycle of 50 percent and are representative of results for other duty cycles.

For both the E10 and E17 systems, the pressures show considerable variation over time, but the mean pressure value is essentially constant. Much of the variation in the instantaneous values (for all parameters) is being caused by the variations in the fuel injector duty cycle, which is being changed each time the systems are turned on. The fact that the average pressure remains constant indicates that the fuel pump and regulators are continuing to function as intended.

Figure 19 indicates that the flow rate for the E10 pump seems to trend upward slightly. This could be related to solvent/mechanical cleaning the components of accumulated deposits from storage at the salvage yard. Figure 20 indicates the flow rate for the E17 diminished somewhat during the testing. However, this pump began testing as a decidedly weaker pump, and it is not clear that degradation in flow was due to E17 and not the accumulation of more cycles on a worn-out pump. Further, a large change can be seen around 400 hrs. This would seem more indicative of a sudden change in mechanical condition, not the gradual decline that would be expected with a fuel-related material incompatibility. This also corresponded to a system shutdown and restart; perhaps one of the fuel supply lines leading to the DAQ rail became slightly kinked.

Also shown in the figures are the rail temperatures, ambient temperatures, and motor electrical current. The ambient temperatures in the test room were not controlled, which allowed the ambient temperature and rail temperatures to vary. The fact that the temperature difference between the rail and ambient was very consistent suggests that the power needed to run the pumps was relatively constant. This conclusion is further supported by the measured motor electrical current, which remained relatively constant for both the E10 and E17 units. For the E17 pump, a material issue such as corrosion should lead to an increase in motor current as the motor labors to overcome increased pump resistance. This supports the belief that there is a mechanical issue with this pump, which persisted from the initial testing.

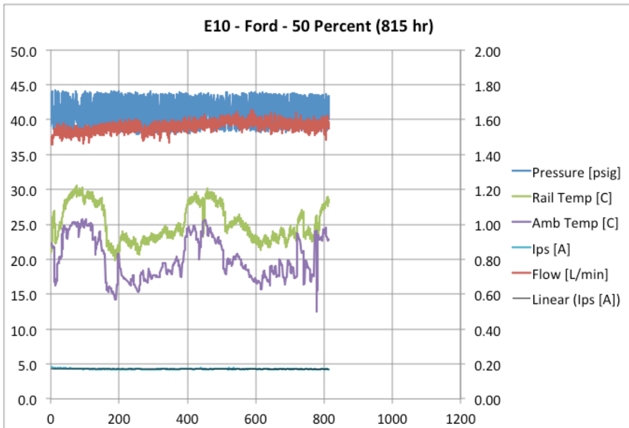


Figure 19: Change in Ford fuel pump operating characteristics with time for E10 at 50% fuel injector duty cycle

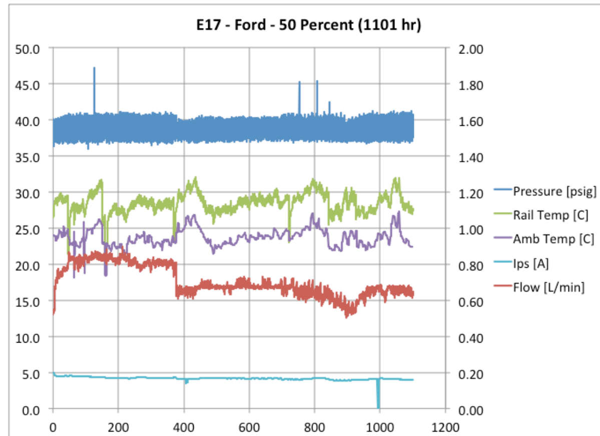


Figure 20: Change in Ford fuel pump operating characteristics as they change over time for E17 at 50% fuel injector duty cycle

4.1.3 Periodic Assessments

4.1.3.1 Fuel Injector Characterization

Representative samples of the fuel injector test data for individual Ford fuel injectors on E10 and E17 are shown Figure 21 and Figure 22, respectively. The complete test data for each fuel injector used can be found in Appendix A.

The Ford injectors remained highly linear over the entire range of injector pulse widths tested. There was little variation in the performance of the injectors over the 800 hours of testing. The E10 injector's initial (0 hr) flow rate appears to be higher than "normal," but the pressure for these tests was 42 psi, while all other tests were conducted at 45 psi due to a variation in the regulator.

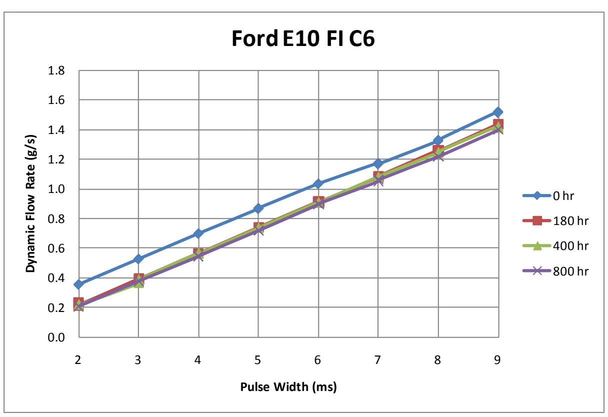


Figure 21: Representative sample of fuel injector test data for a Ford injector on E10

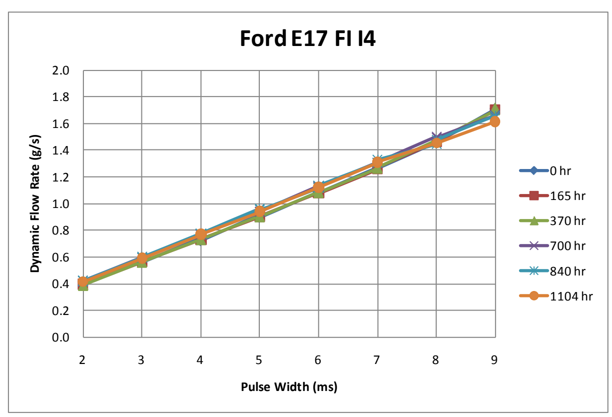


Figure 22: Representative sample of fuel injector test data for a Ford injector on E17

The fuel injector data for each system were determined by averaging the individual injector flow characterization data for the six fuel injectors. The average fuel injector test results for the Ford fuel systems are shown in Figure 23. As can be seen, the static flow rate for the Ford injectors remained similar throughout testing for both the E10 and the E17 injectors. The average injector slopes remained similar throughout testing for both E10 and E17 injectors as well. Further, the magnitude of the static flow rates is similar to that found for the slopes, providing a check of the slope calculations. Clearly, these parameters do not indicate any major deviations when using E17.

After the initial 200 hours of testing, the linear flow range and injector offsets for both systems remain fairly stable for the remainder of testing. Clearly, the E10 injectors "loosened" during the initial stages of the endurance testing, then stabilized; however, a large portion of the change can be attributed to the change in test fuel pressure. These results indicate no unusual degradation when using E17.

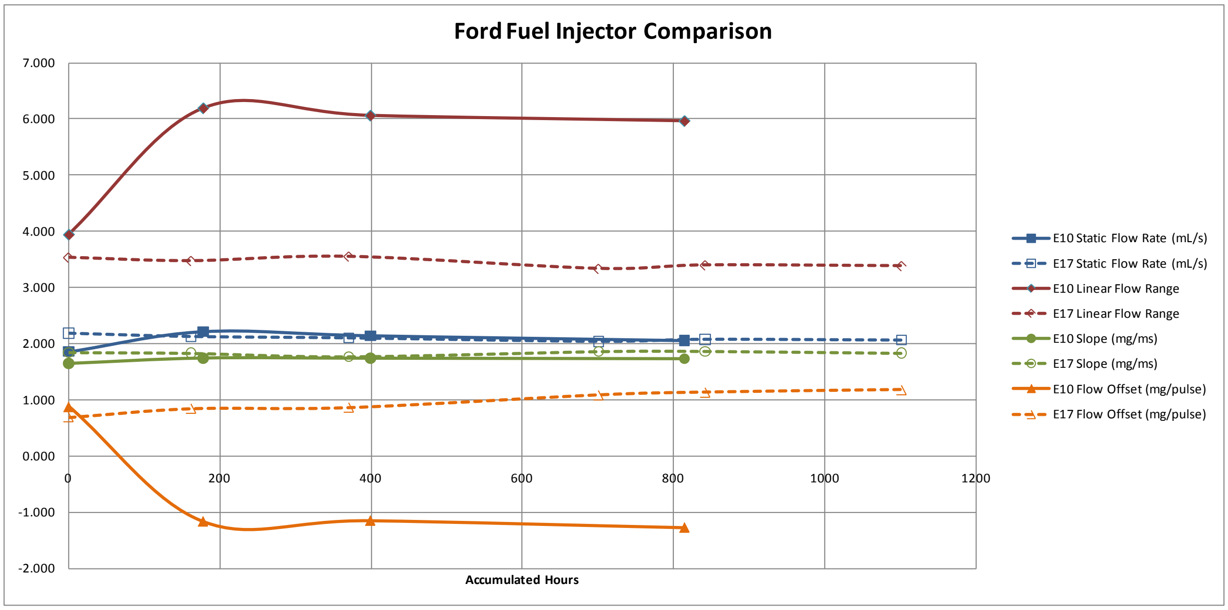


Figure 23: Ford fuel injector comparison

4.1.3.2 Pump Characterization

The results for the periodic maximum flow test (corresponding to 0 percent fuel injector duty cycle) and no flow, or deadhead, pressure tests for the Ford pumps are shown in Figure 24 and Figure 25, respectively. As shown, the E17 pump flow rate was around half of the E10 pump flow rate. Unfortunately, this is also below the minimum flow specifications for a new fuel pump; therefore, this pump had a mechanical issue (i.e., it was worn out). The spare Ford fuel pump operated erratically during testing, sometimes operating and sometimes not. Thus, the spare pump was not used in the test rigs. It was hoped that the E17 pump would "loosen" with use; this appeared to happen at 200 hours. Figure 18 shows the flow rate during endurance testing also declined abruptly upon system restart, indicating a separate issue with the test rig. Unfortunately, the flow rate never reached the minimum level indicated in the new pump specification; however, it is important to note that, on balance, the flow did not degrade substantially during E17 testing. The trend in the E10 pump was slightly upward, which agrees with the results observed during system testing (see Figure 19).

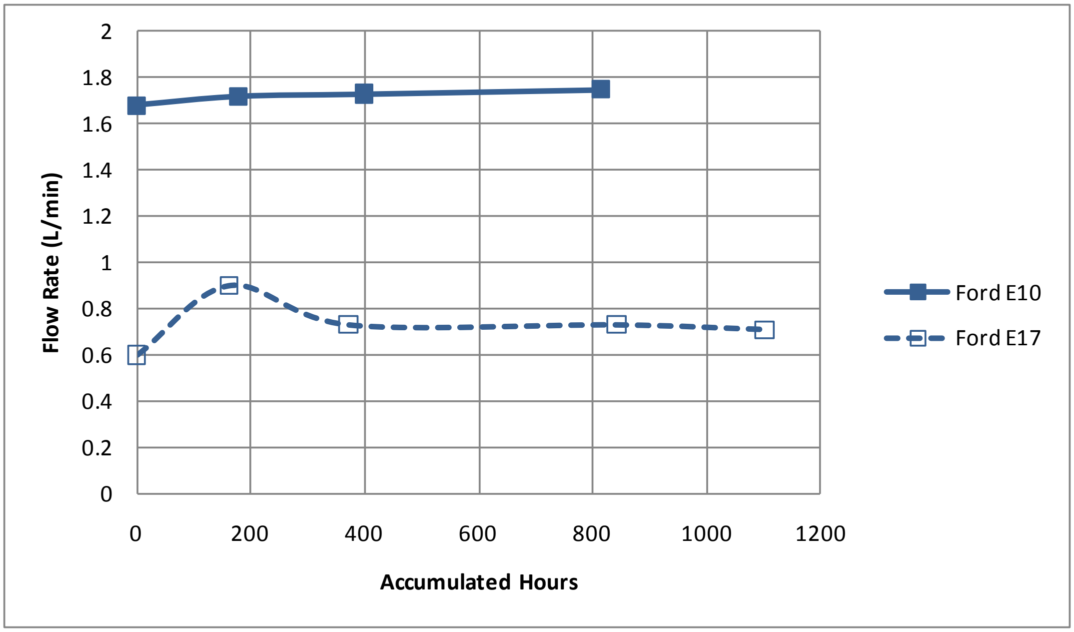


Figure 24: Ford flow rate comparison at a system pressure of approximately 40 psig

The deadhead pump pressures can be seen in Figure 25. The E17 deadhead pressure was around three-quarters of the pressure of the E10 pump. This pressure is below the minimum specification for a new pump; again indicating a pre-existing condition. Beyond the initial tests, the maximum pressure for each pump did not exhibit a substantial change during testing.

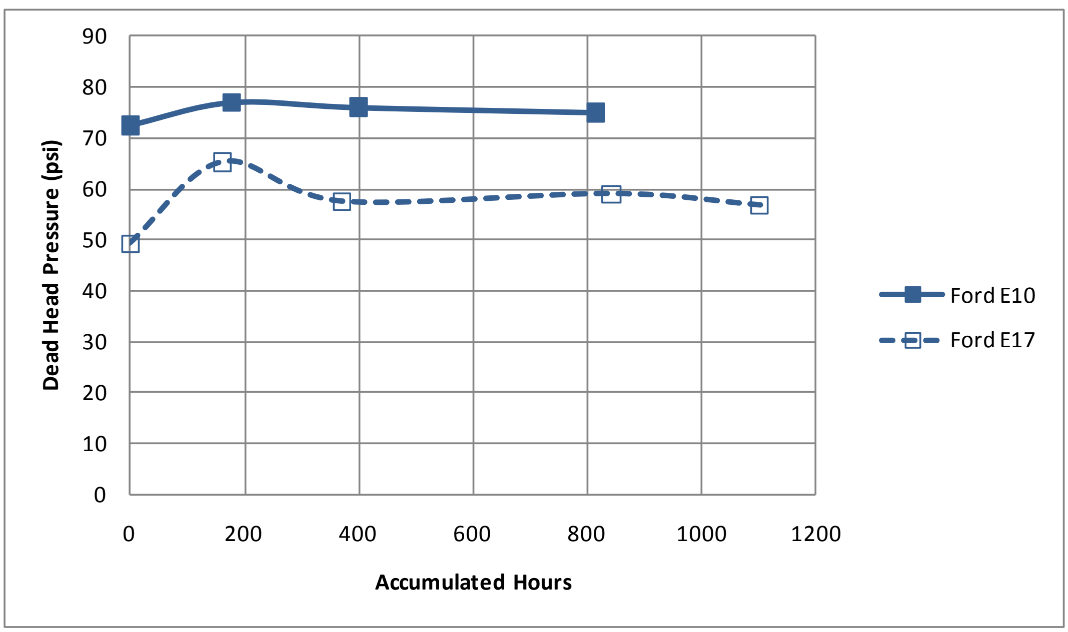


Figure 25: Ford deadhead pressure comparison

4.1.3.3 Fuel Filter Inspection

A representative fuel filter comparison for E10 and E17 units is shown below in Figure 26. There appears to be no difference in the fuel filters between the ethanol blends during the course of testing.

Figure 26: Ford fuel filter representative comparison, E10 left, E17 right

4.1.3.4 Visual Comparison

A visual comparison between the initial and final conditions of the E10 fuel-sending unit is shown in Figure 27 and Figure 28. A comparison between the initial and final conditions of the E17 fuel-sending unit is shown in Figure 29 and Figure 30.

There was little to no change between the initial and final inspections for the E10 and E17 fuel sending units.

Figure 27: Ford E10 fuel sending unit initial photograph

Figure 28: Ford E10 fuel sending unit final photograph

Figure 29: Ford E17 fuel sending unit initial photograph

Figure 30: Ford E17 fuel sending unit final photograph

A comparison between the initial and final conditions of the E10 fuel injectors is shown in Figure 31 through Figure 34. The following observations can be made. Clearly, the injectors were cleaner on the outside after testing. No worn surfaces or residue buildup was noted on any of the injectors.

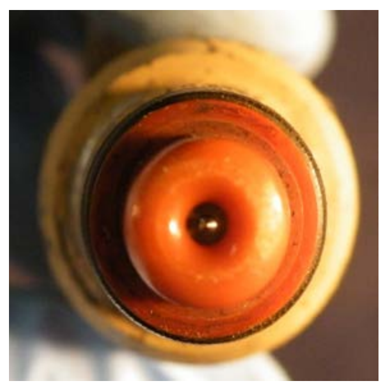


Figure 31: Ford E10 fuel injector outlet; initial inspection

Figure 32: Ford E10 fuel injector outlet; final inspection

Figure 33: Ford E10 fuel injector inlet; initial inspection

Figure 34: Ford E10 fuel injector inlet; final inspection

A comparison between the initial and final conditions of the E17 fuel injectors is shown in Figure 31 through Figure 34. Again, the injectors were cleaner on the outside after testing. Note the initial damage to the “nose” of the injector in Figure 35; this damage increased due to the mechanical stress during removal and installation of the return flow lines for testing. No worn surfaces or residue buildup that could be attributed to ethanol were noted on any on the injectors.

Figure 35: Ford E17 fuel injector outlet; initial inspection

Figure 36: Ford E17 fuel injector outlet; final inspection

Figure 37: Ford E17 fuel injector inlet; initial inspection

Figure 38: Ford E17 fuel injector inlet; final inspection

4.2 General Motors Results

4.2.1 Failures

No failure occurred for either of the two fuel systems during testing. The fuel system operating on E10 ran for 1,669 hours, while the E17 fuel system ran for 1,113 hours.

4.2.2 Endurance Testing Performance Analysis

Figure 39 and Figure 40 show the operating points (pressure and flow) for the GM fuel pumps during system testing for the E10 and E17 fuels, respectively. Both pumps were able to provide a consistent regulated pressure of 45 psi (nominal) throughout the duration of the testing. Both pumps were able to consistently supply a high flow rate, although the E10 and E17 pumps produced similar average flow rates (1.21 and 1.16 L/min, respectively), the range of flows produced by the E17 pump (0.8–1.4 L/min) was more consistent that the flows produced by the E10 pump (0.8–1.7 L/min). This distribution in flow values for the GM pumps was the reverse of that observed in the Ford pumps and suggests that this variation is more related to a distribution of pump performance in individual pumps rather than related to the ethanol content of the fuel.

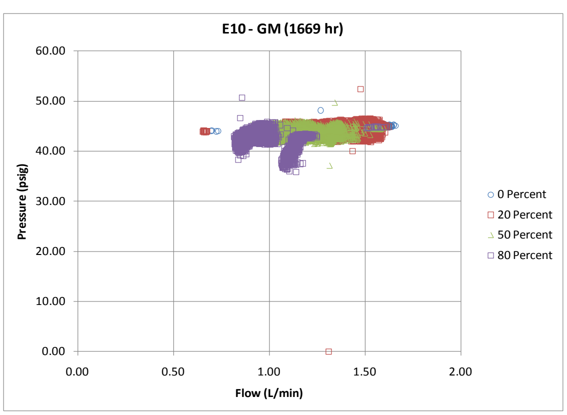


Figure 39: GM fuel pump operating points during system testing on E10

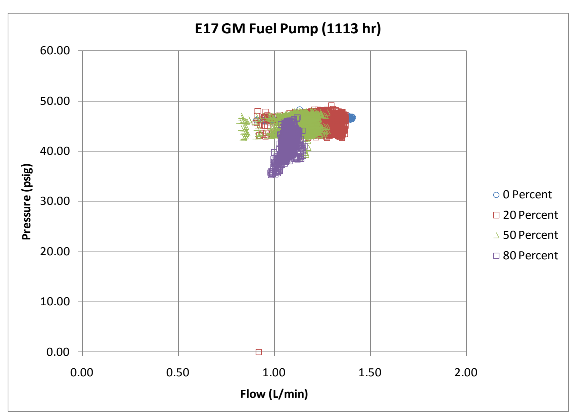


Figure 40: GM fuel pump operating points during system testing on E17

Figure 41 and Figure 42 show the GM fuel pump operating characteristics as they vary over time for the E10 and E17 fuels, respectively. It can be seen that the average pressure maintained by the fuel pumps and regulators in both systems is very constant over time and actually increases slightly in both. The flow rate for the E10 was high (1.35 L/min) for the first 800 hours before it fell to a more typical value (at least as compared to the E17 flow rate), which varied in the range of 1.0–1.2 L/min. Temperature and electric current trends are similar to those found in the Ford systems. There is no obvious trend in the flow (or other) data to suggest any degradation in pump performance that would be associated with the use of E17.

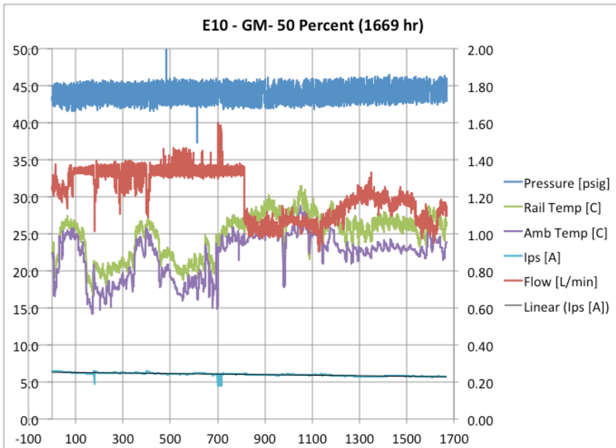


Figure 41: GM fuel pump operating characteristics as they change over time for E10 at 50% fuel injector duty cycle

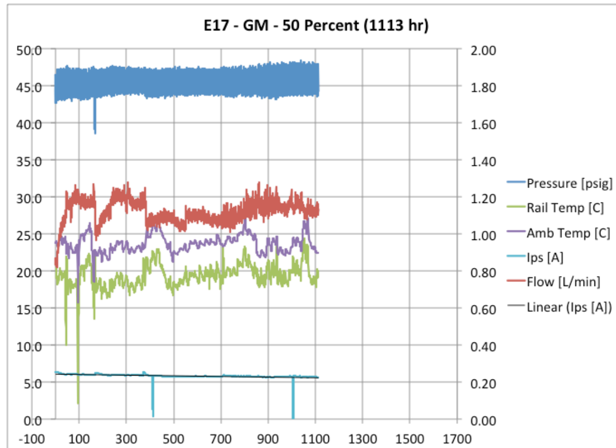


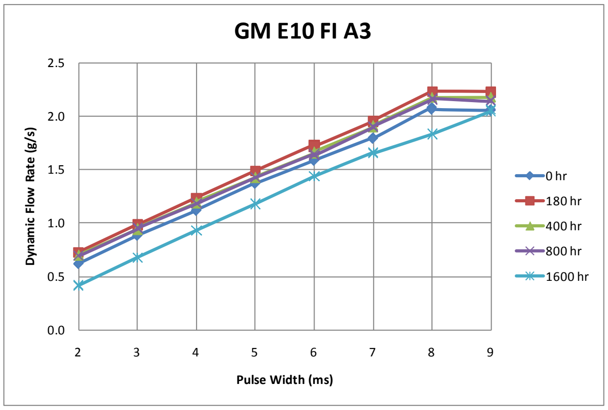
Figure 42: GM fuel pump operating characteristics as they change over time for E17 at 50% fuel injector duty cycle

4.2.3 Periodic Assessments

4.2.3.1 Fuel Injector Characterization

Representative samples of the fuel injector test data for GM injectors on E10 and E17 are shown in Figure 43 and Figure 44, respectively. The complete test data for each fuel injector used is included in Appendix A.

The flow rates for the E10 injectors remain linear up to a pulse width of 8 ms before falling off. There is a steady decrease in the flow at every pulse width over time. The E17 injector flow rates remain linear up to a pulse width of 7–8 ms before again falling off. In the linear range, the flow rates for the E17 injectors remain very consistent over time; however, in the nonlinear range, there is a significant decrease in the flow rates over time.



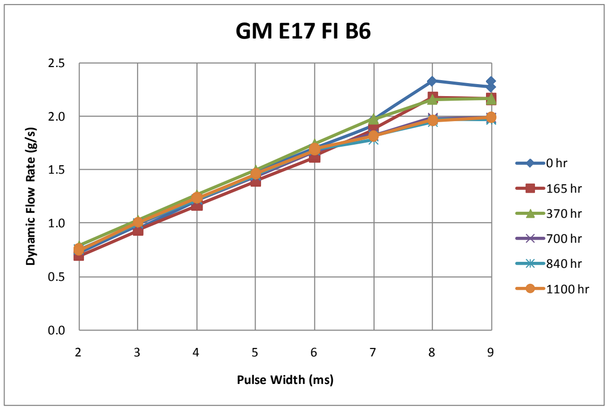


Figure 43: Representative sample of fuel injector test data for a GM injector on E10

Figure 44: Representative sample of fuel injector test data for a GM injector on E17

The fuel injector data for each system were determined by averaging the individual injector flow characterization data for the six fuel injectors. The average fuel injector test results for the GM fuel systems are shown in Figure 45. As can be seen, the static flow rate for the GM injectors remained similar throughout testing for both the E10 and the E17 injectors. The average injector slopes remained similar throughout testing for both E10 and E17 injectors as well. Further, the magnitude of the static flow rates is similar to that found for the slopes, providing a check of the slope calculations. These parameters do not indicate any major deviations when using E17.

The linear flow range and injector offsets for both systems remain fairly stable until 1,100 hours of testing. The LFR and offsets for the E10 unit then slightly improved during the check at 1,600 hrs, indicating less non-linearity. The LFR and Offset parameters do not indicate any unusual degradation when using E17.

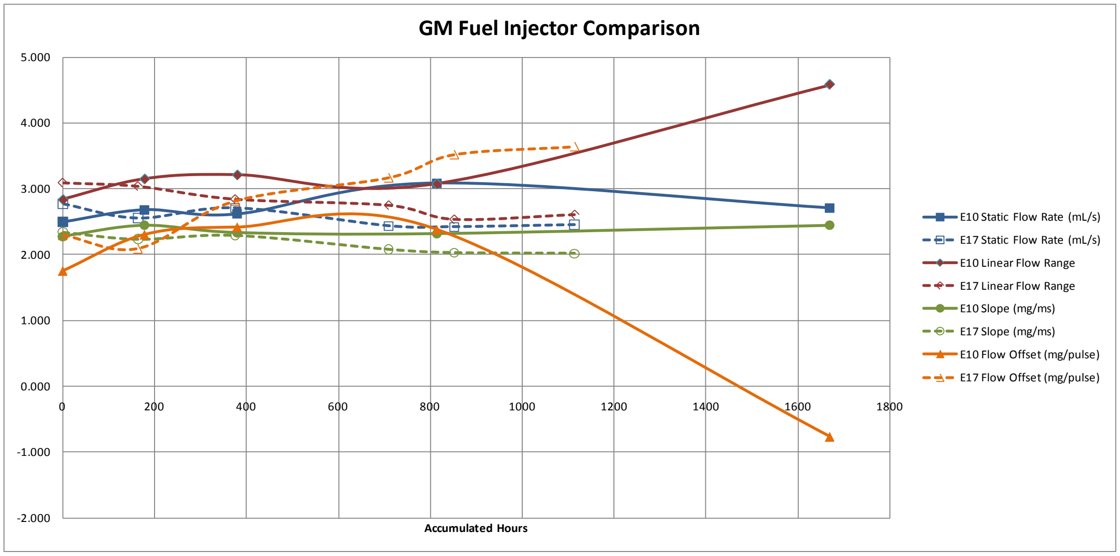


Figure 45: GM fuel injector comparison

4.2.3.2 Pump Characterization

The results for the periodic 0-percent duty cycle flow test and maximum deadhead pressure tests for the GM pumps are shown in Figure 46 and Figure 47, respectively. The E10 pump shows some decrease in flow over time. The E17 pump flow rate is lower than the E10 pump flow rate; however, both pump flows are within manufacturer specifications. The E17 pump apparently loosened during the initial phases of testing as is shown by the large increase in flow after the first testing interval. This is indicative of a pump that had either pre-existing corrosion, or, more likely, was just dirty from a period of disuse in the salvage yard. After the initial increase in flow, the remaining flow rates stabilized, showing no sign of degradation.

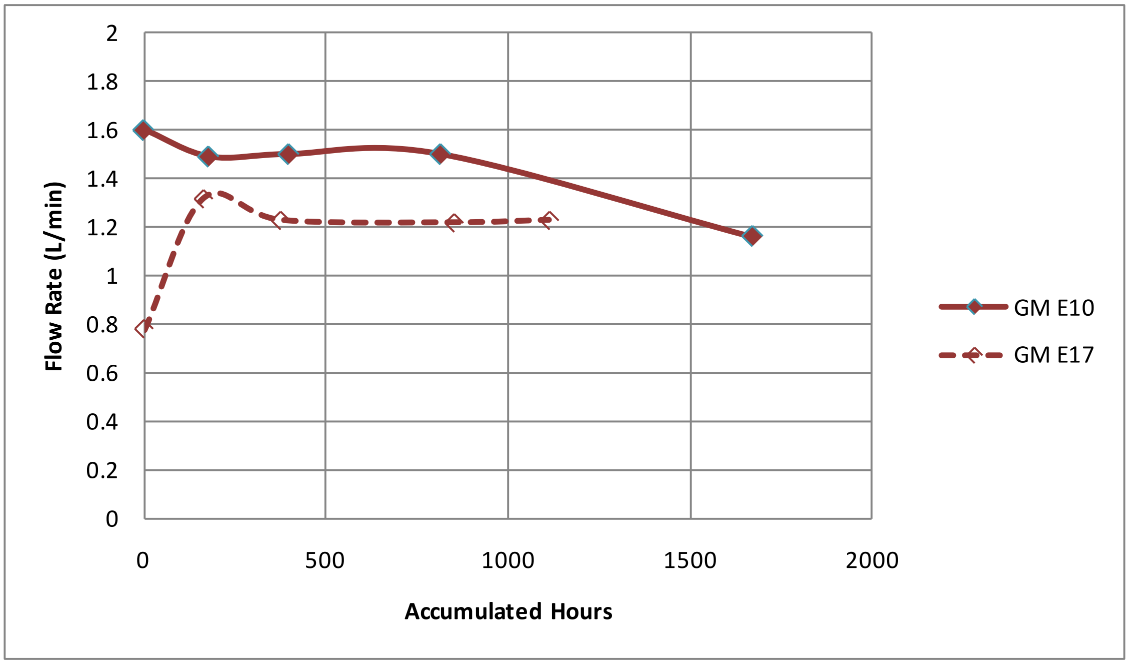


Figure 46: GM Flow rate comparison a system pressure of approximately 45 psig

The E10 and E17 pumps deadhead pressure are shown in Figure 47. The pressure for the E10 pump remained somewhat steady. As with the flow, the E17 pump showed a dramatic improvement in pressure during the first test interval. This suggests that the pump loosened up with time and then stabilized for the remainder of the testing.

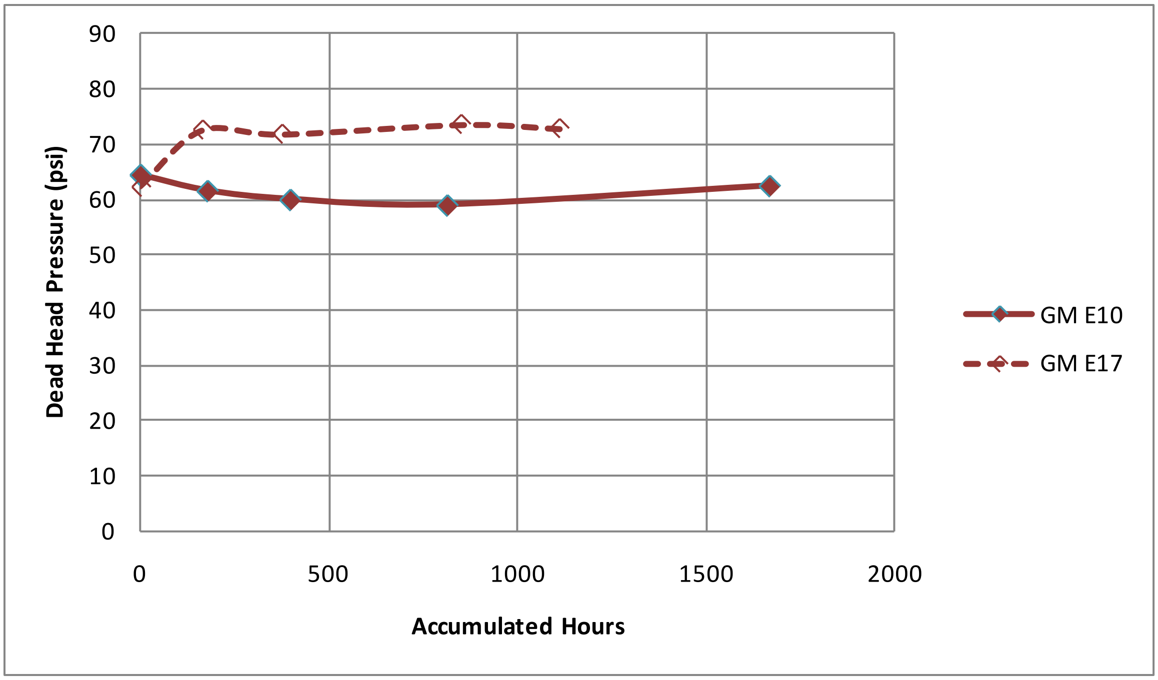


Figure 47: GM deadhead pressure comparison

4.2.3.3 Fuel Filter Inspection

Representative fuel filters for the E10 and E17 units are shown in Figure 48. There appears to be no difference in between the ethanol blends and during the course of testing.

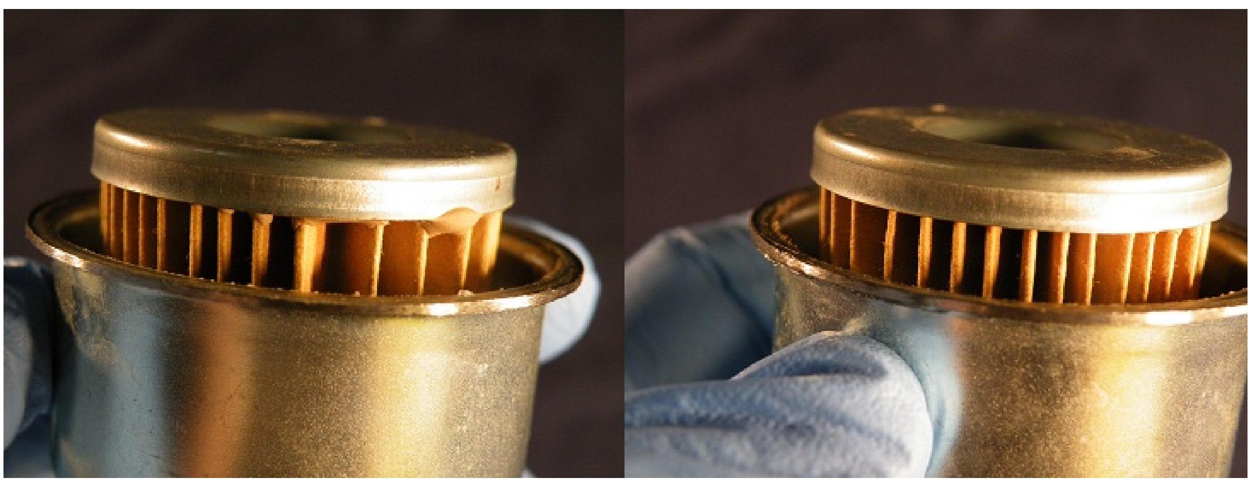


Figure 48: GM fuel filter representative comparison, E10 left, E17 right

4.2.3.4 Visual Comparison

There was little to no change between the initial and final inspections for the E10 and E17 fuel sending units, fuel rails, and fuel injectors. A comparison between the initial and final inspections of the E10 fuel sending units is shown in Figure 49 and Figure 50. A comparison between the initial and final inspections of the E17 fuel sending units is shown in Figure 51 and Figure 52.

Figure 49: GM E10 fuel sending unit; initial inspection

Figure 50: GM E10 fuel sending unit; final inspection

Figure 51: GM E17 fuel sending unit; initial inspection

Figure 52: **GM E17 fuel sending unit; final inspection**

A comparison between the E10 fuel injectors is shown in Figure 53 through Figure 56. The injectors were cleaner on the outside after testing. No worn surfaces or residue buildup was noted on any on the injectors.

Figure 53: GM E10 fuel injector outlet; initial inspection

Figure 54: GM E10 fuel injector inlet; initial inspection

Figure 55: GM E10 fuel injector outlet; final inspection

Figure 56: GM E10 fuel injector inlet; final inspection

A comparison between the initial and final inspections of the E17 fuel injectors is shown in Figure 57 through Figure 60. The injectors were cleaner on the outside after testing. No worn surfaces or residue buildup was noted on any on the injectors.

Figure 57: GM E17 fuel injector outlet; initial inspection

Figure 58: GM E17 fuel injector outlet; final inspection

Figure 59: GM E17 fuel injector inlet; initial inspection

Figure 60: GM E17 fuel injector inlet; final inspection

4.3 Toyota Results

4.3.1 Failures

No failure occurred during testing of the Toyota fuel system components during testing of the two ethanol bends after 1,664 hours for the unit using the E10 blend, and 1,104 hours for the unit using the E17 blend.

4.3.2 Endurance Testing Performance Analysis

Figure 61and Figure 62 show the operating points (pressure and flow) for the Toyota fuel pumps during system testing for the E10 and E17 fuels, respectively. Both pumps showed considerable variation in both pressure and flow during systems testing. Much of this variation seems to be inherent in the design of the Toyota fuel system because each system behaved in this way from the beginning of the testing. The variation in system operation makes it difficult to determine if the pump performance is degrading over time. It should be noted that the manufacturer's specifications for the Toyota fuel pumps were lower than those of the Ford or GM units, which may be contributing to the variation.

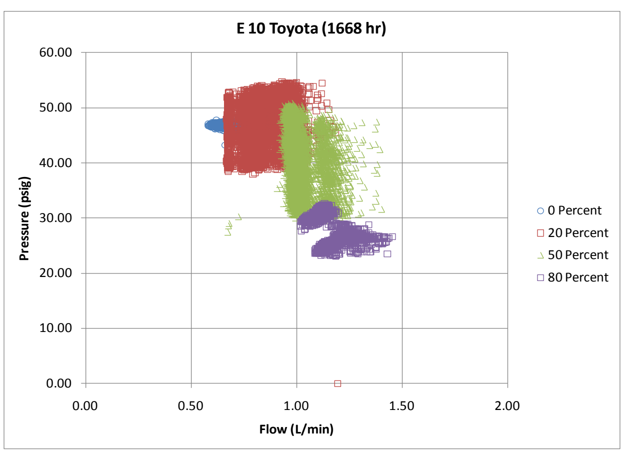


Figure 61: Toyota fuel pump operating points during system testing on E10

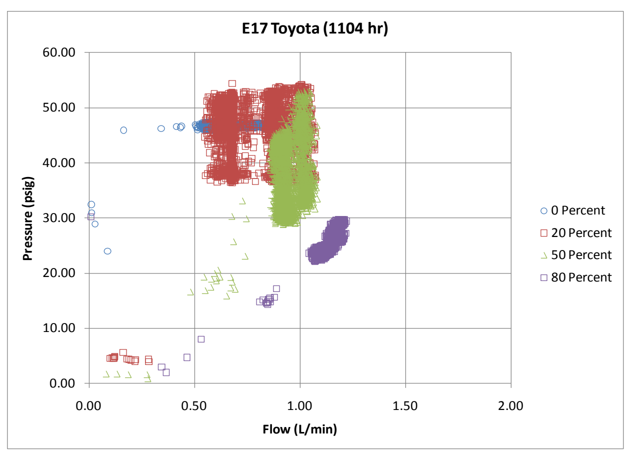


Figure 62: Toyota fuel pump operating points during system testing on E17

Figure 63 and Figure 64 show the Toyota fuel pump operating characteristics as they vary over time for the E10 and E17 fuels, respectively. Unlike the Ford and GM fuel systems, the Toyota fuel systems showed significant variation in the pressure and flow during endurance testing. Both the E10 and E17 systems show much higher variation in instantaneous pressure values with a spread of greater than 15 psi compared to a spread of less than 5 psi for both the Ford and GM systems. The average pressure in the E10 unit is both up and down, and there appears to be a corresponding variation in flow rates; when the flow rate goes up, the pressure drops and vice versa. The flow also shows a slight degradation with time. The average pressure and flow in the E17 system both appear to be trending downward with use. The temperatures and motor electrical current follow the same trends as the Ford and GM units.

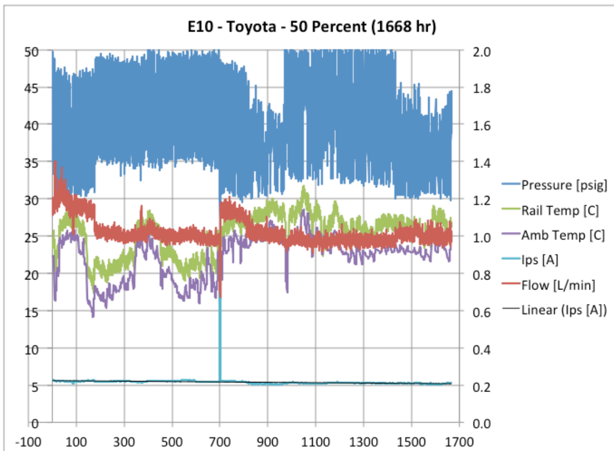


Figure 63: Toyota fuel pump operating characteristics as they change over time for E10 at 50% fuel injector duty cycle

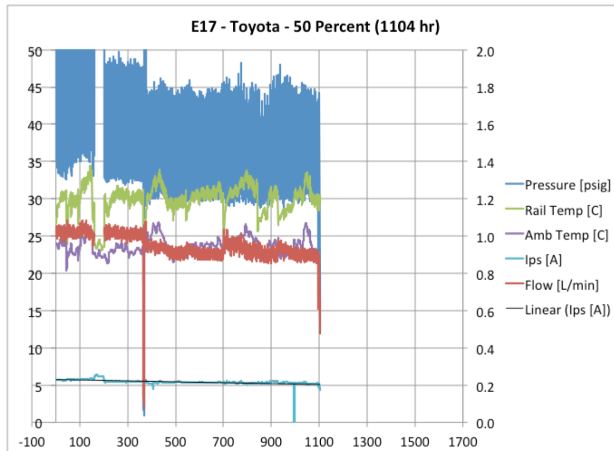


Figure 64: Toyota fuel pump operating characteristics as they change over time for E17 at 50% fuel injector duty cycle

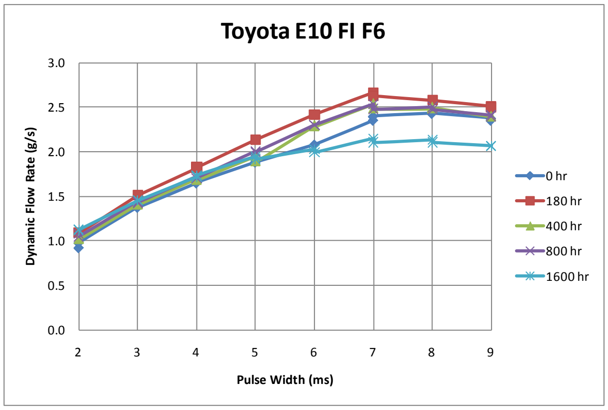
Although the variation in the data makes it hard to quantify, the data seem to support the hypothesis that the performance of the Toyota fuel pump with the E17 is degrading slightly with usage. This hypothesis can be checked by examination of the periodic maximum flow and maximum pressure test data.

4.3.3 Periodic Assessments

4.3.3.1 Fuel Injector Characterization

Representative samples of the fuel injector test data for Toyota injectors on E10 and E17 are shown Figure 65 and Figure 66, respectively. The complete test data for each fuel injector used are included in Appendix A.

The flow rates for the E10 injectors are nonlinear over most of the pulse width range. This is behavior is independent of test time. Both the E10 and E17 injectors are showing significant reduction in the flow rates at high pulse width over time.



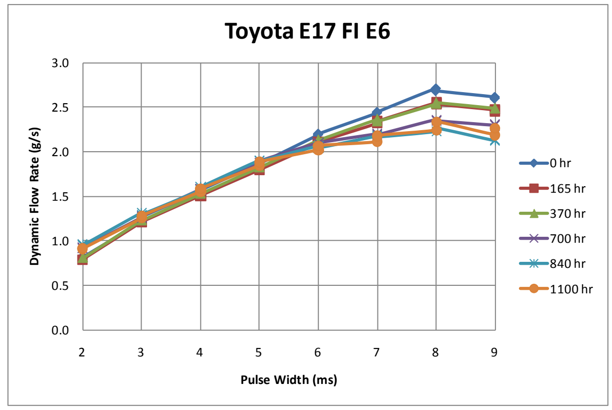


Figure 65: Representative sample of fuel injector test data for a Toyota Injector on E10.

Figure 66: Representative sample of fuel injector test data for a Toyota Injector on E17.

The fuel injector data for each system were determined by averaging the individual injector flow characterization data for the six fuel injectors. The average fuel injector test results for the Toyota fuel systems are shown in Figure 67. The static flow rate for the Toyota injectors remained similar throughout testing for both the E10 and the E17 injectors. The average injector slopes remained similar throughout testing for both E10 and E17 injectors as well. Further, the magnitude of the static flow rates is similar to that found for the slopes, providing a check of the slope calculations. However, all of the values tended to degrade over time; however, these parameters do not indicate any major differences between E17 and E10 systems.

The linear flow range and injector offsets for both the E10 and E17 systems are quite poor due to the non-linearity of these injectors (see Figure 65 and Figure 66). It is not known whether the extreme non-linearity in the Toyota injectors is by design or due to extreme use prior to testing. The increase in flow offset and decrease in LFR are consistent with the degradation in the fuel injector dynamic flow rates at high pulse width. This suggests that both the E10 and E17 fuel injectors were wearing out.

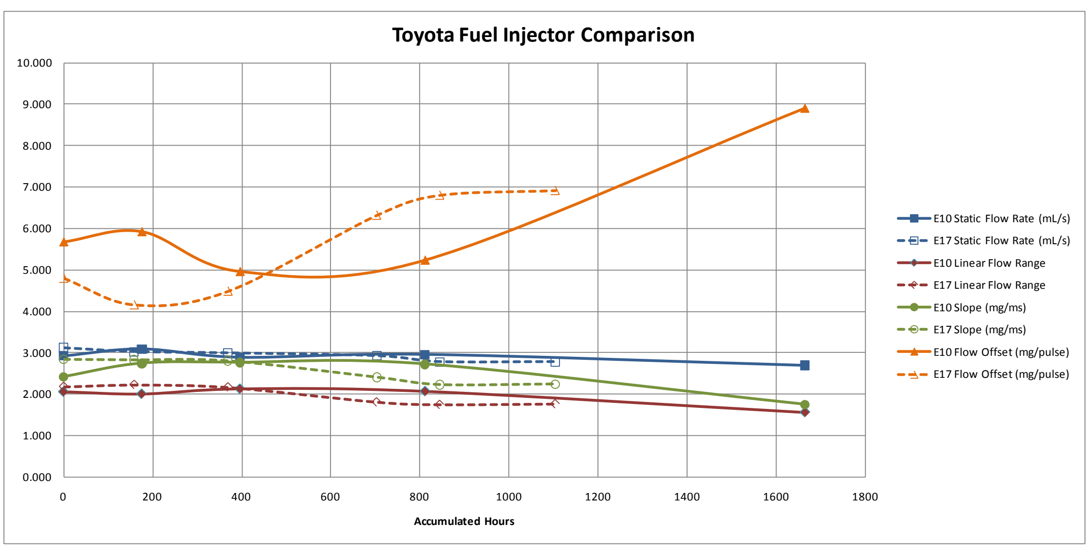


Figure 67: Toyota fuel injector comparison

4.3.3.2 Pump Characterization

The results for the periodic 0-percent duty cycle flow test and maximum deadhead pressure tests for the Toyota fuel pumps are shown in Figure 68 and Figure 69, respectively. The E17 flow rate is usually lower than the E10 pump. The two Toyota fuel pumps both saw an improvement in their flow rates once they were broken in; however, unlike the Ford and GM system, there seemed to be a significant reduction in the flow rates over time for both the E10 and E17 fuels. The reduction in flow was worse for the E17 pump than for the E10 pump. This can be seen in Figure 68.

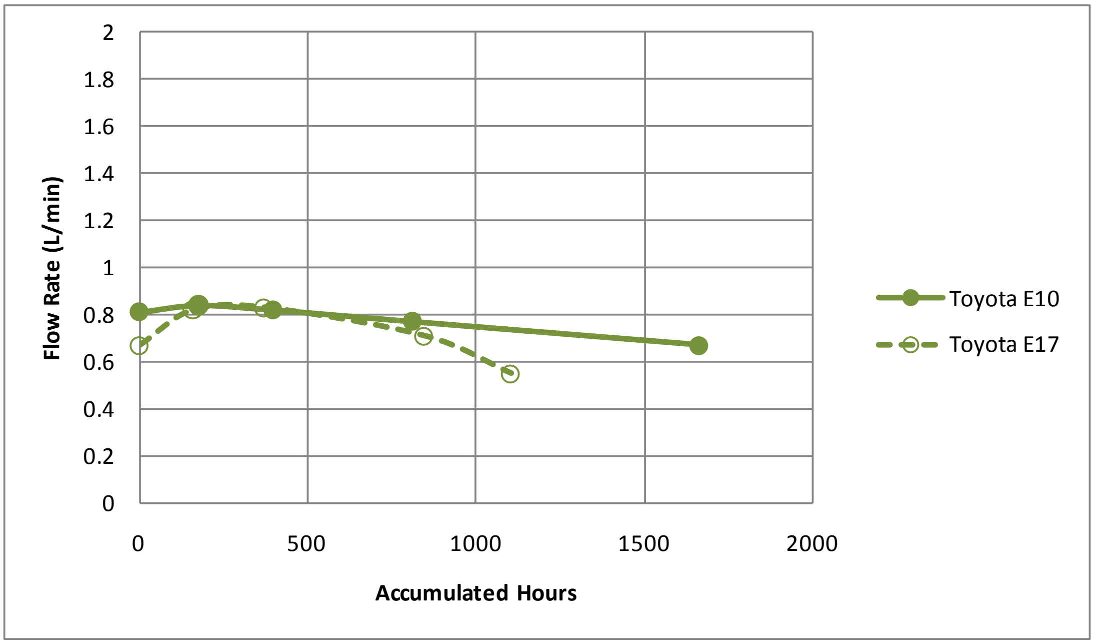


Figure 68: Toyota flow rate comparison at a system pressure of approximately 47 psig

The deadhead pressure is similar for both the E10 and E17 pumps. The E10 and E17 pump deadhead pressures both degrade slightly over time. The E17 pressure degrades by a slightly higher amount than the E10 pump pressure, as seen in Figure 69.

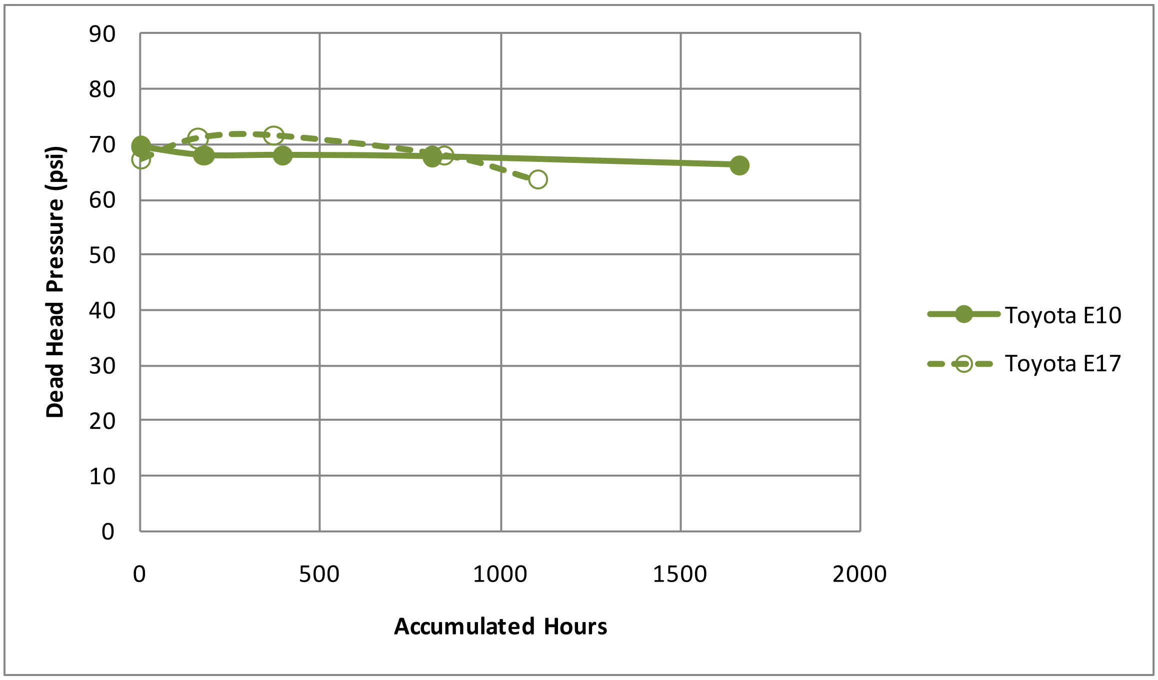


Figure 69: Toyota deadhead pressure comparison

4.3.3.3 Fuel Filter Inspection

Representative fuel filter inspections are shown for the E10 and E17 units in Figure 70. There appears to be no difference in between the ethanol blends and during the course of testing.

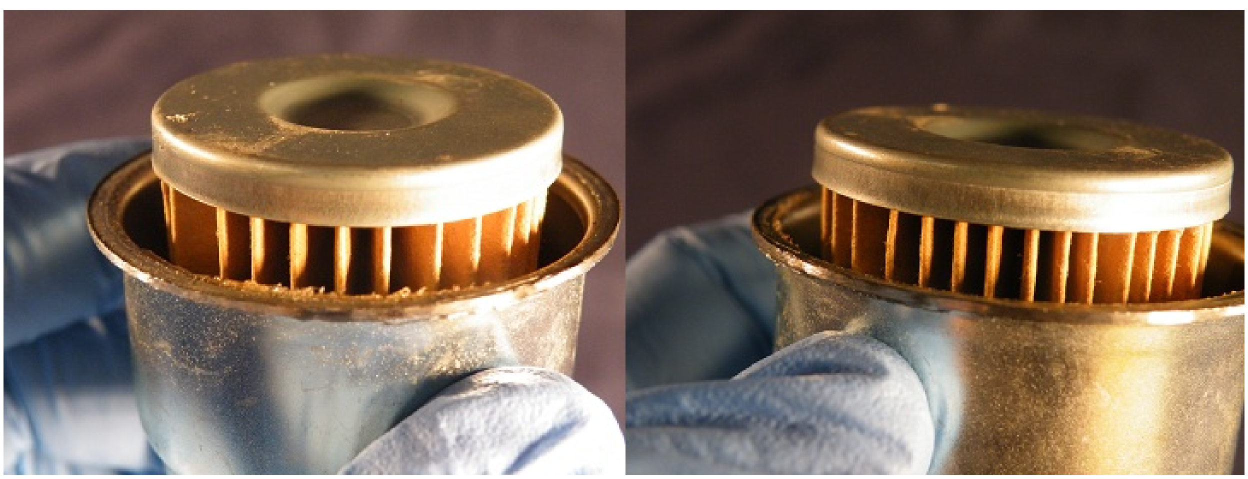


Figure 70: Toyota fuel filter representative comparison, E10 left, E17 right

4.3.3.4 Visual Comparison

There was little to no change between the initial and final inspections for the E10 and E17 fuel sending units, fuel rails, and fuel injectors. A comparison between the initial and final inspections of the E10 fuel sending unit is shown in Figure 71 and Figure 72. A comparison between the initial and final inspections of the E17 fuel sending unit is shown in Figure 73 and Figure 74.

Figure 71: Toyota E10 fuel sending unit: initial inspection

Figure 72: Toyota E10 fuel sending unit: final inspection

Figure 73: Toyota E17 fuel sending unit: initial inspection

Figure 74: Toyota E17 fuel sending unit: final inspection

Comparison between the initial and final conditions of the E10 fuel injectors are shown in Figure 75 through Figure 78. The injectors were cleaner on the outside after testing. The outlet O-rings on all Toyota injectors tended to wear/break due to hose installation and removal during periodic injector testing. No worn surfaces or residue buildup was noted on any on the injectors.

Figure 75: Toyota E10 fuel injector outlet; initial inspection

Figure 76: Toyota E10 fuel injector outlet; final inspection

Figure 77: Toyota E10 fuel injector inlet; initial inspection

Figure 78: Toyota E10 fuel injector inlet; final inspection

A comparison between the E17 fuel injectors is shown in Figure 79 through Figure 80. Their condition was similar to that of the E10 injectors. No worn surfaces or residue buildup was noted on any on the injectors.

Figure 79: Toyota E17 fuel injector outlet; initial inspection

Figure 80: Toyota E17 fuel injector outlet; final inspection

Figure 81: Toyota E17 fuel injector inlet; initial inspection

Figure 82: Toyota E17 fuel injector inlet; final inspection

4.4 Fuel Analyses

A single batch of commercial pump grade E10 was purchased in drums to complete all fuel system testing. E17 was made by splash blending this E10 with fuel grade ethanol meeting ASTM D4806 specifications. Analyses of the initial test fuels and periodic fuel samples were performed by Southwest Research Institute. The fuel analytical methods and descriptions are listed in Table 4 along with the results from the baseline fuels analyses. The actual ethanol content of E17 was 19.5 vol% (average of three replicate D5599 analyses) which, while high, is within the D5599 method error of ±2.6 vol% for E17.

Table 4: Fuel Analysis Methods and Baseline Fuel Characterization

ASTM Method	Fuel Property / Analysis	E10	E17
D5599	Ethanol Content (Vol%)	10.4	19.5
D5188	Vapor/Liquid Ratio = 20 (°F)	120.5	117.3
D5191	Reid Vapor Pressure (psi)	10.98	11.92
D6304	Karl Fischer Water Content (ppm)	1,051	2,325
D381	Gums (Unwashed, mg/100mL)	17.5	17.5
D1613	Acidity as Acetic Acid (mg KOH/g)	0.013	0.009
D130	Copper Strip Corrosion	1A = pass	1A = pass
D2624	Conductivity (pS/m)	>1,999 = pass	>1,999 = pass
D525	Oxidation Stability (min)	1440 = pass	1440 = pass
D5185	Metals by ICP-AES	Appendix B	Appendix B
D7328	Sulfate in Fuel by IC (total, ppm)	0.4	0.0
D7328	Chloride in Fuel by IC (total, ppm)	0.0	0.0
D3703	Peroxide Content (mg/kg)	0.68	0.91
D4176	Appearance (color)	Clear/Bright	Clear/Bright
D5453*	Sulfur Content (ppm)	36.4	30.5

*Initial fuels only

Fuel samples were taken periodically from the fuel system rigs to evaluate any changes in fuel properties. The in-use hours for the fuels and for the test rigs are shown in the first two rows of Table 5, followed by selected fuel properties measured. One evident fuel property change was the consistent increase in Unwashed Gum during the initial 196 – 216 hours on a test fuel. These increases ranged from a factor of 3 to 8 during this period. It is postulated that these increases were in part the result of solvating deposits on the fuel system components that initial cleaning in Stoddard solvent did not remove. The fact that subsequent samples obtained after draining and refilling the fuel system with fresh fuel tended to have smaller increases of Unwashed Gum (factors of 2 to 5.5) supports this hypothesis (see Notes under Table 5 for fuel change times).

The fuels' Reid vapor pressure (RVP) tended to decrease with time, as shown in Figure 83. Note that these data are compiled from different test rig fuel fills, i.e., they are not the same charge of fuels over the time period shown. The fuel systems were equipped with pressure relief valves, the headspaces were blanketed with inert gas, and the injectors sprayed into tubes above the headspace, so some vapor losses were expected. RVP generally decreased more quickly for E17 than for E10, consistent with the E17's higher amount of volatile ethanol and higher initial RVP. Both E10 and E17 Toyota systems had higher than expected RVP losses (-3.5 to -7.9 psi from the baseline fuels), and fuel from the E17 GM system sampled at 216 hours on May 2, 2011, showed a -4.6 psi loss from the baseline fuel. Incomplete sealing of these systems after removing their lids for fuel sampling or pump performance testing might explain one or all of these large RVP losses. However, it is puzzling that both Toyota fuel systems lost the most RVP, so other causes may be involved that cannot be determined from the available data.

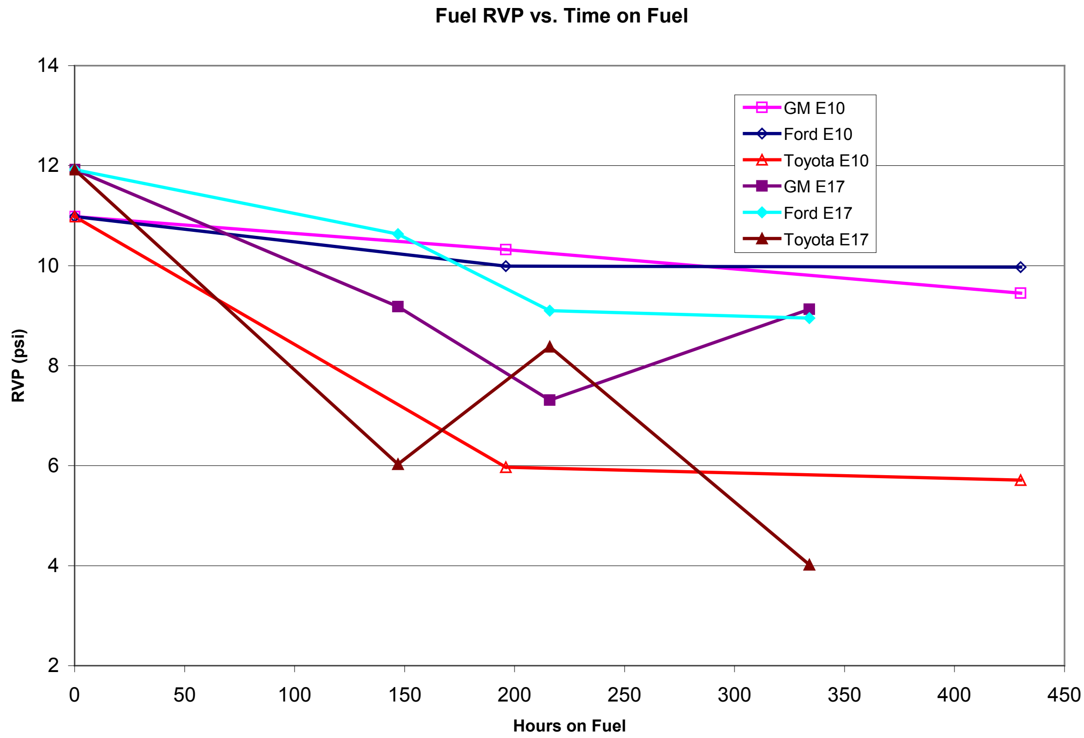


Figure 83: Fuel Reid vapor pressure as a function of time in recirculation (Note: data series are not the same fuel charge for each time step).

The temperature of the measured vapor/liquid ratio = 20 (V/L_{20}) inversely reflects the RVP losses, i.e. the temperature of V/L_{20} increases as a result of fewer volatile compounds in the fuel, which also leads to lower RVP. The V/L_{20} temperature data in Table 5 show the Toyota systems consistently had the highest volatile component losses; again the reasons for this are unclear.

All fuel samples passed the oxidation stability test method D525, except one sample taken from the Toyota E17 test rig at 385 hours into that test. ASTM gasoline standard D4818 requires an oxidation stability period of at least 240 hours by method D525. All other samples reached 1440 hours without issue, however this Toyota E17 sample only reached 123 hours. This fuel sample instability does not appear to correlate with any other fuel changes so the reason for the oxidation instability is unclear. The ASTM D5185 analyses for metals revealed that there were no significant changes in any fuel samples. Thus there was no detectable difference between E10 and E17 in terms of metal wear or corrosion. The complete data set detailing the metal analyzed and all fuel analyses are in Appendix D.

Table 5: Selected Fuel Properties of Test Fuel Samples

GM Fuel Systems							
Fuel Property \ Sample ID →	**Baseline E10**	**E10: 2-19-11**	**E10: 4-4-11**	**Baseline E17**	**E17: 5-2-11**	**E17: 5-25-11**	**E17: 06-02-11**
Time on Fuel (hrs)	0	196	430[A]	0	216[B]	334[C]	147[D]
Time on Fuel System (hrs)	0	196	853	0	385	720	867
Ethanol Content (Vol %)	10.4	8.9	8.0	19.5	21.1	16.3	15.6
Karl Fischer Water Content (ppm)	1051	890	745	2325	2787	2152	1831
Peroxide Content (mg/kg)	0.68	1.14	1.37	0.91	0.46	0	0
Acidity as Acetic Acid (mg KOH/g)	0.013	0.024	0.014	0.009	0.017	0.017	0.013
Unwashed Gum (mg/100 mL)	17.5	124	72	17.5	106	60	39
Vapor Pressure (RVP; psi)	10.98	10.32	9.45	11.92	7.31	9.13	9.18
Vapor/Liquid Ratio = 20 (^oF)	120.5	123.7	148.5	117.3	141.2	131.5	131.3
Ford Fuel Systems							
Fuel Property \ Sample ID →	**Baseline E10**	**E10: 2-19-11**	**E10: 4-4-11**	**Baseline E17**	**E17: 5-2-11**	**E17: 5-25-11**	**E17: 06-02-11**
Time on Fuel (hrs)	0	196	430[A]	0	216[B]	334[C]	147[D]
Time on Fuel System (hrs)	0	196	853	0	385	720	867
Ethanol Content (Vol %)	10.4	9.6	10.6	19.5	20.1	18.4	15.4
Karl Fischer Water Content (ppm)	1051	923	913	2325	2361	2447	1975
Peroxide Content (mg/kg)	0.68	0.68	1.49	0.91	0.46	0	0
Acidity as Acetic Acid (mg KOH/g)	0.013	0.023	0.015	0.009	0.015	0.016	0.012
Unwashed Gum (mg/100 mL)	17.5	81	54.5	17.5	60.5	58	30.5
Vapor Pressure (RVP; psi)	10.98	9.99	9.97	11.92	9.1	8.95	10.63
Vapor/Liquid Ratio = 20 (^oF)	120.5	126.4	142.4	117.3	131.4	133.2	123.3
Toyota Fuel Systems							
Fuel Property \ Sample ID →	**Baseline E10**	**E10: 2-19-11**	**E10: 4-4-11**	**Baseline E17**	**E17: 5-2-11**	**E17: 5-25-11**	**E17: 06-02-11**
Time on Fuel (hrs)	0	196	430[A]	0	216[B]	334[C]	147[D]
Time on Fuel System (hrs)	0	196	853	0	385	720	867
Ethanol Content (Vol %)	10.4	9.2	9.0	19.5	20.4	19.8	16.5
Karl Fischer Water Content (ppm)	1051	834	797	2325	2454	2545	2500
Peroxide Content (mg/kg)	0.68	1.37	1.71	0.91	0.57	0.68	0.57
Acidity as Acetic Acid (mg KOH/g)	0.013	0.034	0.021	0.009	0.013	0.020	0.018
Unwashed Gum (mg/100 mL)	17.5	142.5	90	17.5	55.5	95.5	42
Vapor Pressure (RVP; psi)	10.98	5.97	5.71	11.92	8.38	4.02	6.03
Vapor/Liquid Ratio = 20 (^oF)	120.5	151.4	150.2	117.3	135.9	164.5	147.7

Notes on fuel draining and refilling: A- Fresh E10 fill at 423 hrs into system test. B- Fresh E17 fill at 169 hrs into system test. C- Fresh E17 fill at 385 hrs into system test. D- Fresh E17 fill at 720 hrs into system test.

5 Conclusions and Recommendations

5.1 Interpretation of Aging Test Results

A rating system was developed to try to quantify the changes in physical measurements and observations made during the different phases of testing. The following scale was used: no change in performance/condition during testing received a zero, improved performance/condition received a positive number, and degradation in performance/condition merited a negative rating. Larger magnitudes were indicative of more severe change.

Table 6 summarizes the results for the fuel pumps. Using this scale, both the Ford and GM fuel pumps showed little negative change during testing. However, as noted previously, the Ford E17 pump had a pre-existing condition as evidenced by its low pressure and flow rates, and it did show a slight degradation in performance.

Both of the Toyota fuel pumps demonstrated degradation in performance during testing. Further, the degradation of the E17 pump was more pronounced than that of the E10 pump, potentially indicating additional problems when using E17. However, due to the performance degradation in both pumps, it is not clear whether E17 had any real negative effect or if both pumps were simply worn out.

All of the fuel pumps except the Ford E10 performed somewhat below the manufacturer's specifications for new pumps (see Table 3) for minimum flow at rated pressures. The deadhead pressures for the Ford and Toyota pumps remained within the manufacturer's specifications; however, the GM pumps fell slightly below the minimum specification. It must be noted that the pressure specifications for the GM pumps were the highest of the pumps tested. All of this is to be expected as these pumps were procured from a salvage yard and not from running vehicles. These were old pumps with unknown usage histories. In addition, since only two pumps were tested for each manufacturer, the sample size is very small, leading to large standard deviations.

Table 6: Summary of Fuel Pump Ratings

	Characterization: Deadhead Pressure	Characterization: Flow Rate	Endurance Performance	Visual Comparison	Fuel-Related Failures	Total
Ford E10	0	1	0	0	0	1
Ford E17	0	0	-1	0	0	-1
GM E10	0	-1	0	0	0	-1
GM E17	0	0	0	0	0	0
Toyota E10	-1	-1	-1	0	0	-3
Toyota E17	-2	-2	-2	0	0	-6

A similar effort was undertaken for the fuel injectors. Table 7 summarizes the results for the injectors. The operational history for all of the injectors is unknown; therefore, a conscious attempt was made to mix injectors from all sources in the test rigs. Six injectors were tested in each aging rig.

The Ford and GM injectors showed little change over the aging tests. In fact, the GM injectors operated using E10 demonstrated slight increases in performance. The Toyota injectors did show degradation in performance during the aging tests, although quantifying the results is difficult as the injectors were not linear over much of the operating range. This non-linearity complicates the typical calculations used to produce linear flow parameters such as the slope, offset, and linear flow range. The static flow rates and injector slopes both decreased slightly over time for both sets of injectors, indicating reduced flow performance over time. The decrease in LFR and increase in flow offset are manifestations of the decrease in dynamic flow rate at high pulse width and indicate a significant decrease in injector performance over time. However, since the decrease in performance is similar for both the E10 and E17 injectors, it is difficult to conclude that E17 exerted any influence on the Toyota injectors. That degradation in flow is similar for both sets, leading to the conclusion that the injectors were probably in poor condition due to their prior history.

Table 7: Fuel Injector Ratings Comparison

	Character-ization: Static Flow Rate	Character-ization: Slope	Character-ization: Linear Flow Range	Character-ization: Offset	Visual Compar-ison	Fuel-Related Failures	Total
Ford E10	0	0	0	0	0	0	0
Ford E17	0	0	0	0	0	0	0
GM E10	1	0	1	1	0	0	3
GM E17	0	0	0	0	0	0	0
Toyota E10	-1	-1	-2	-2	0	0	-6
Toyota E17	-1	-1	-2	-2	0	0	-6

The effect of the unknown history makes it difficult to evaluate the results. For example, all of the components tested are at least 10 years old. According to the U.S. Department of Energy (2011), the average number of miles driven per year is around 12,000. This would mean that components used could already have been operated for 120,000 miles. Further, the aging test added additional operational time. To relate this to potential miles driven, the 10-ms injector cycling period corresponds to an engine speed of about 3,000 rpm. If a vehicle is traveling on the highway at this engine speed in top gear, the vehicle would be traveling at a high rate of speed (perhaps 75–85 mph). Operating the units for 30 minutes out of a 90-minute cycle will then add an equivalent mileage of 25,000–30,000 miles per 1,000 test hours. Therefore, the fuel pumps, rails, and regulators could potentially have an equivalent mileage of over 150,000 miles when reaching the 1,000-hour milestone. The question then becomes one of which components will fail first, the fuel system components or some other vehicle system.

Overall, based on the results of both the fuel pump testing and the fuel injector testing, there *might* be slightly more degradation in the Toyota fuel system component performance when using E17; however, this result is not certain due to the many factors described previously. Clearly, none of the systems indicated any major incompatibilities to E17.

5.2 Recommendations

The unknown fuel component histories add some uncertainty to the aging tests. Acquiring fuel system components from operational legacy vehicles would potentially reduce the uncertainty. The vehicle odometer readings would provide valuable operational detail. In addition, the vehicles could undergo emissions and performance testing prior to testing to estimate the condition of the fuel system. Finally, none of the internal portions of the components would have been exposed to weather, etc., while stored in salvage yards. However, this approach is not without problems as there is a high likelihood that at least some of these components would already have been replaced. This means that these components would have an unknown time in service. Further, the materials and construction of aftermarket components are often changed from the original parts; thus, they may have been designed for modern ethanol-blended fuel.

Acquiring a larger sample size would also reduce the effects of unknown history and would also improve the precision of the results gathered from running vehicles.

Operating the fuel system components under more severe conditions would also provide more details of the effect of E17. For example, operating at elevated temperatures might increase the chemical susceptibility of the fuel system materials. Also, more aggressive fuel formulations could be used.

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List of Acronyms

ASTM	ASTM International, formerly known as the American Society for Testing and Materials, is an international organization that develops testing and material standards.
cRIO	a compact real-time input/output system sold by National Instruments. The system is capable of both data acquisition and control. The name is also abbreviated at CompactRIO.
DI	digital input
DIO	digital input/out
E10	a fuel mixture consisting of 90% gasoline and 10% ethanol, by volume.
E17	a fuel mixture consisting of 83% gasoline and 17% ethanol, by volume.
E20	a fuel mixture consisting of 80% gasoline and 20% ethanol, by volume.
FI	fuel injector, the device used to inject fuel into an engine cylinder or manifold
GE Druck	Brand name for a line of pressure calibrators sold by General Electric
GM	General Motors Corporation
Ips	current to the power supply
LFR	linear flow range; for a fuel injector it is the range of pulse widths for which flow output is linearly related to the pulse width.
NI	National Instruments, the company that manufactures and sells the cRIO data acquisition and control system.
PTFE	polytetrafluoroethylene , a fluoropolymer of tetrafluoroethylene. It is most well known by the DuPont brand name Teflon.
PVC	polyvinyl chloride, a thermoset polymer
PW	pulse width, the length of time (typically in ms) that a fuel injector is held on
SAE	SAE International, formerly known as the Society of Automotive Engineers, is an international organization that supports the profession of automotive engineering, in part by developing recommended standard practices
SSR	solid-state relay, a device used to turn on/off an electrical connection
TC	thermocouple, a sensor used to measure temperature
TTL	transistor-transistor logic, a common class of digital circuits
V6	An engine style with six cylinders arranged in two banks of three cylinders. When viewed from the end the two banks are aligned in the shape of the letter “V.”
VDC	voltage (direct current)
VIN	vehicle identification number

Appendix A

Fuel Injector - Periodic Testing

This appendix presents data collected on the fuel injectors during the periodic performance tests. The number of hours accumulated on the fuel systems at the time of the performance tests is summarized in Table A1. Data are provided for each injector and includes: static flow rate (mL/s), slope (mg/ms), flow offset (mg/pulse), and laminar flow range at each test point. Also provided are plots of the dynamic flow rate vs. pulse width for each injector and at each test point.

Table A1: Periodic Test Points for Fuel Pumps and Injectors

Test Number	Ford E10	GM E10	Toyota E10	Ford E17	GM E17	Toyota E17
	Hours	Hours	Hours	Hours	Hours	Hours
1	0	0	0	0	0	0
2	178	178	176	162	164	158
3	399	398	396	371	375	369
4	815	814	812	701	709	703
5	---	1,669	1,668	842	851	845
6	---	---	---	1,101	1,113	1,104

Data are provided for each set of fuel injectors in the following order:

- Ford E10
- Ford E17
- GM E10
- GM E17
- Toyota E10
- Toyota E17

For each set of fuel injectors, the data are presented in the following order:

- Tabular results of static flow, slope, offset, and LFR at each test point
- Plots of static flow, slope, offset, and LFR vs. time
- Plot of dynamic flow rate vs. pulse width

Table A2: Ford E10 Fuel Injector Data

Ford E10				
0	**hours**			
Injector	**Static Flow Rate**	**Slope**	**Flow Offset**	**LFR**
I1	1.833	1.608	0.441	4.248
I2	1.867	1.614	0.322	4.458
K2	1.800	1.790	2.946	2.406
C1	1.900	1.642	0.450	4.244
C4	1.867	1.605	0.603	4.057
C6	1.883	1.617	0.514	4.239
Average	**1.858**	**1.646**	**0.879**	**3.942**
Std. Dev.	**0.036**	**0.072**	**1.017**	**0.763**
177.8	**hours**			
Injector	**Static Flow Rate**	**Slope**	**Flow Offset**	**LFR**
I1	2.200	1.717	-1.416	6.872
I2	2.233	1.752	-1.514	7.198
K2	2.183	1.788	-0.171	3.543
C1	2.250	1.734	-1.259	6.513
C4	2.217	1.734	-1.379	6.642
C6	2.217	1.726	-1.254	6.355
Average	2.217	1.742	-1.166	6.187
Std. Dev.	**0.024**	**0.025**	**0.497**	**1.328**
399	**hours**			
Injector	**Static Flow Rate**	**Slope**	**Flow Offset**	**LFR**
I1	2.133	1.717	-1.372	6.788
I2	2.167	1.738	-1.443	7.045
K2	2.100	1.763	-0.112	3.464
C1	2.183	1.735	-1.235	6.436
C4	2.133	1.727	-1.329	6.577
C6	2.150	1.752	-1.419	6.032
Average	**2.144**	**1.739**	**-1.152**	**6.057**
Std. Dev.	**0.029**	**0.017**	**0.515**	**1.315**
814.5	**hours**			
Injector	**Static Flow Rate**	**Slope**	**Flow Offset**	**LFR**
I1	2.050	1.717	-1.519	6.988
I2	2.067	1.733	-1.586	5.157
K2	2.017	1.764	-0.386	3.571
C1	2.083	1.735	-1.363	6.612
C4	2.067	1.718	-1.435	6.729
C6	2.067	1.712	-1.366	6.708
Average	**2.058**	**1.730**	**-1.276**	**5.961**
Std. Dev.	**0.023**	**0.019**	**0.445**	**1.341**

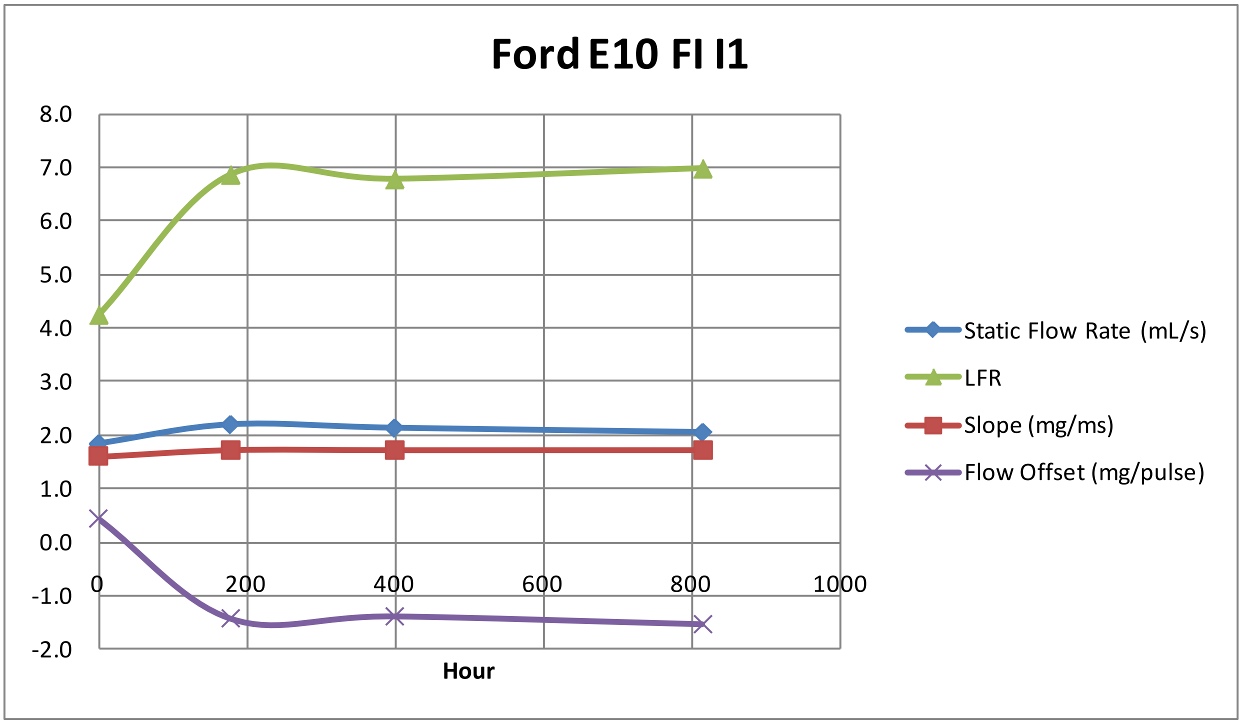

Figure A1: Significant parameters of Ford E10 fuel injector I1

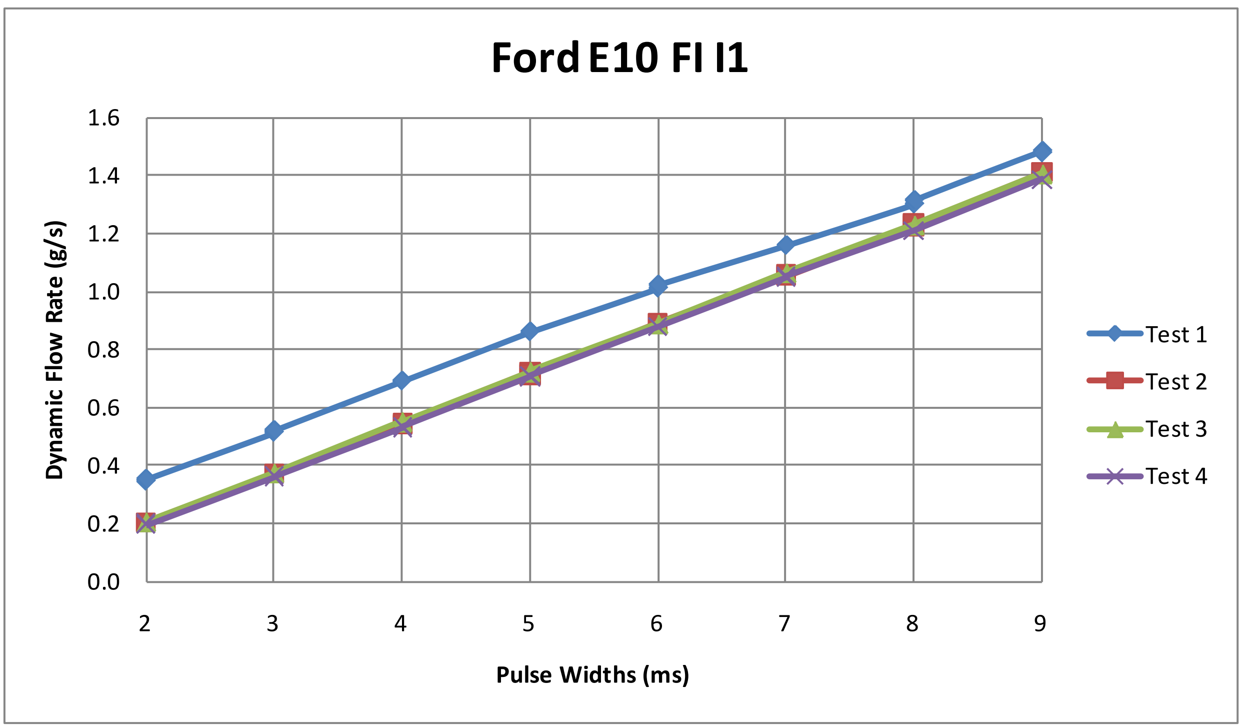

Figure A2: Dynamic flow rate of Ford E10 fuel injector I1

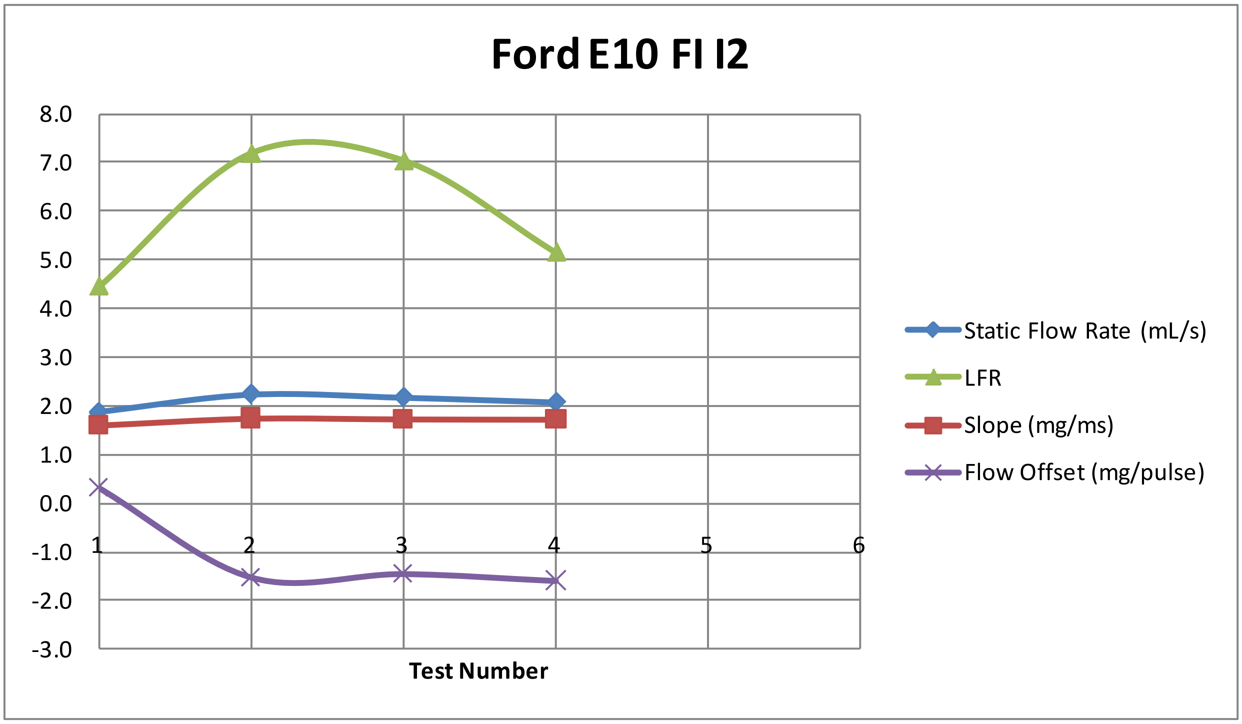

Figure A3: Significant parameters of Ford E10 fuel injector I2

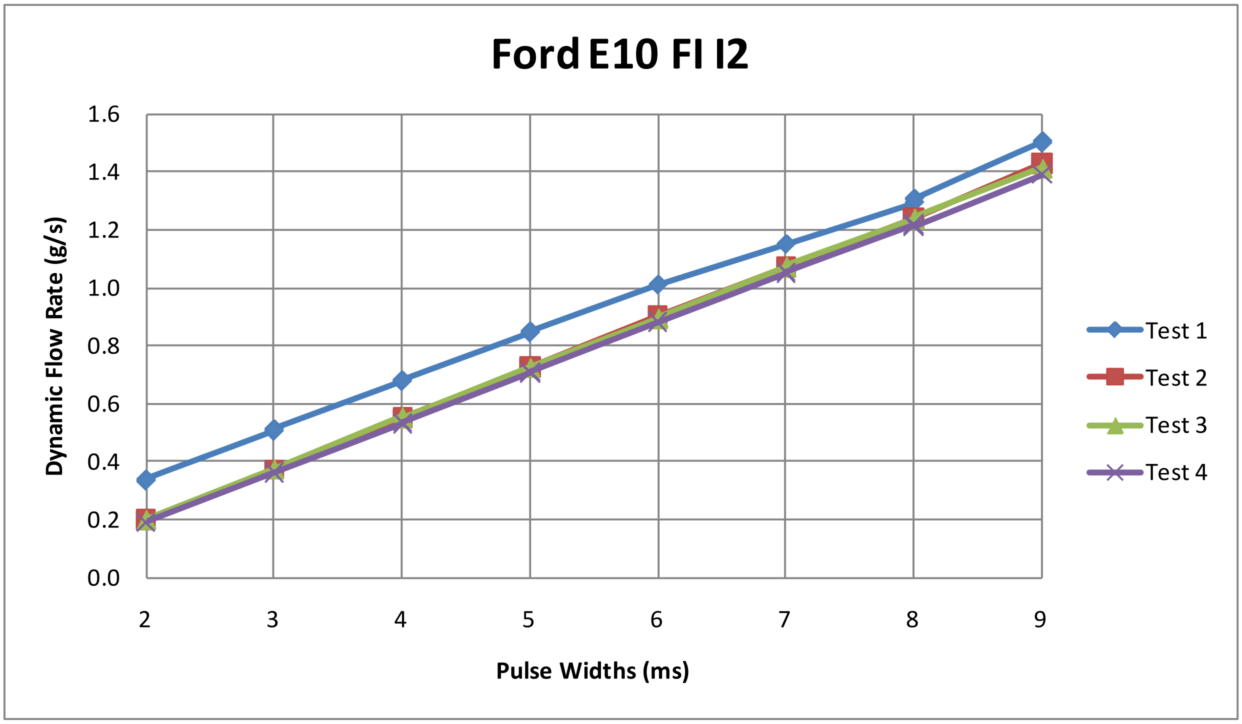

Figure A4: Dynamic flow rate of Ford E10 fuel injector I2

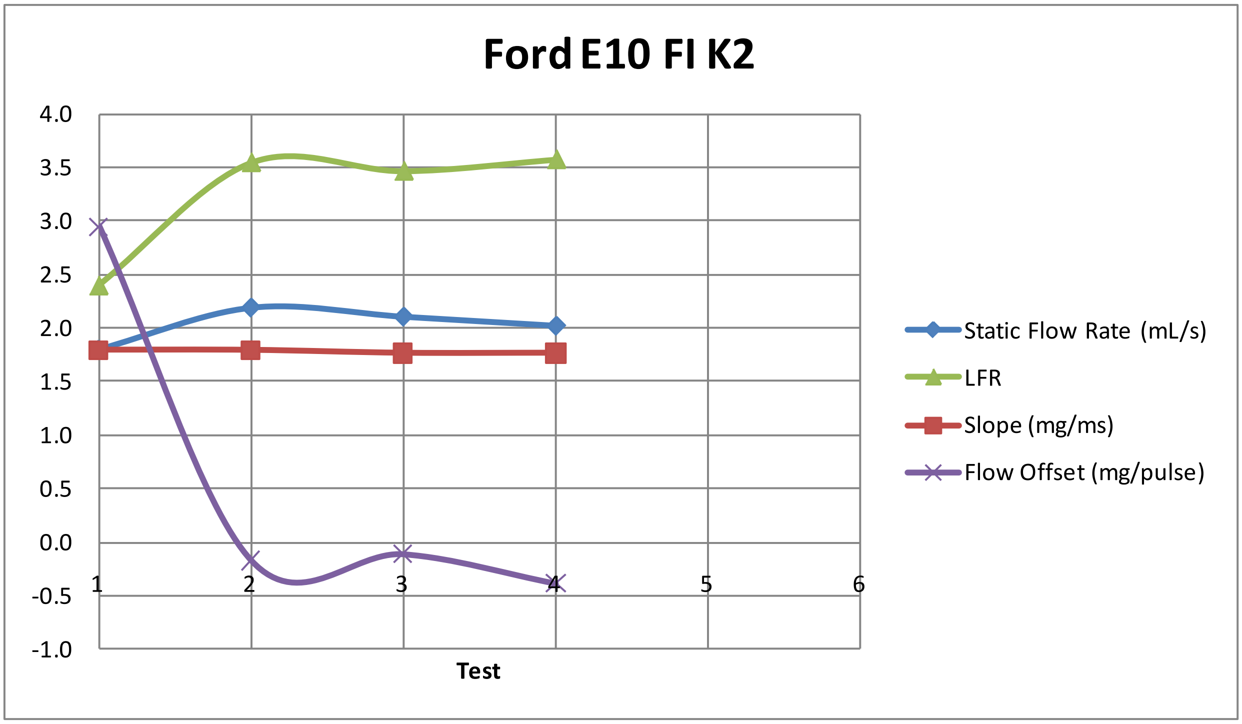

Figure A5: Significant parameters of Ford E10 fuel injector K2

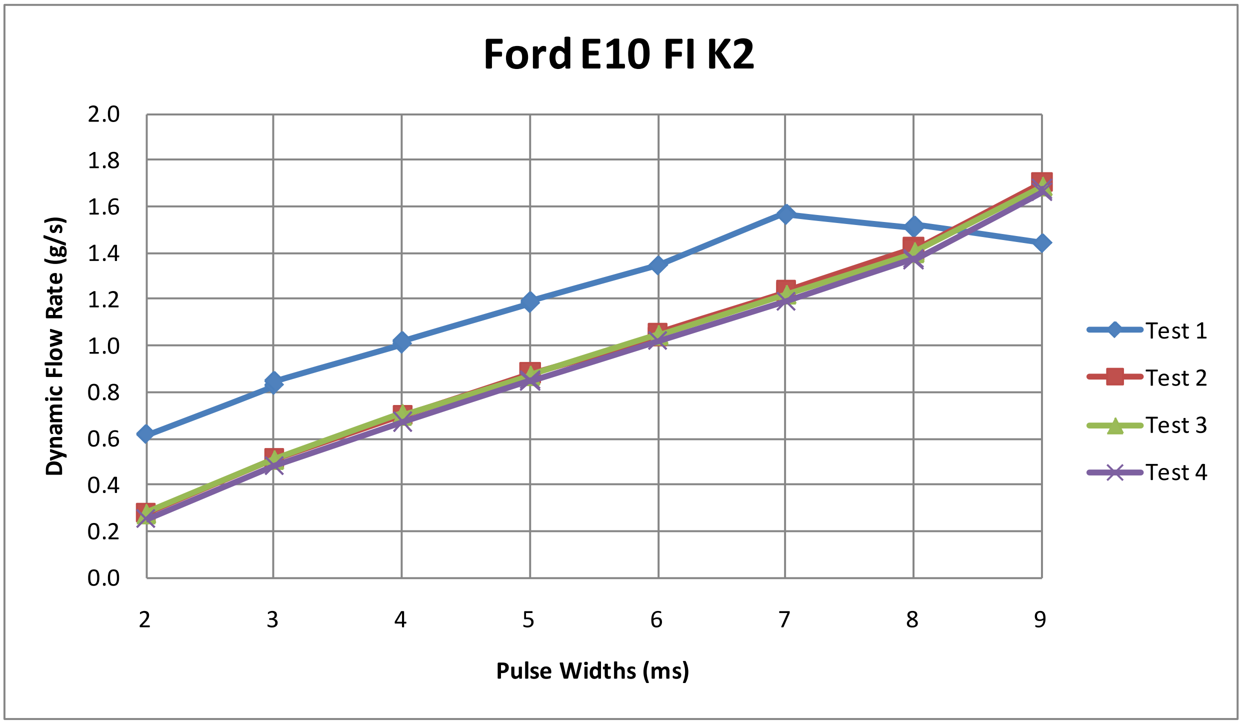

Figure A6: Dynamic flow rate of Ford E10 fuel injector K2

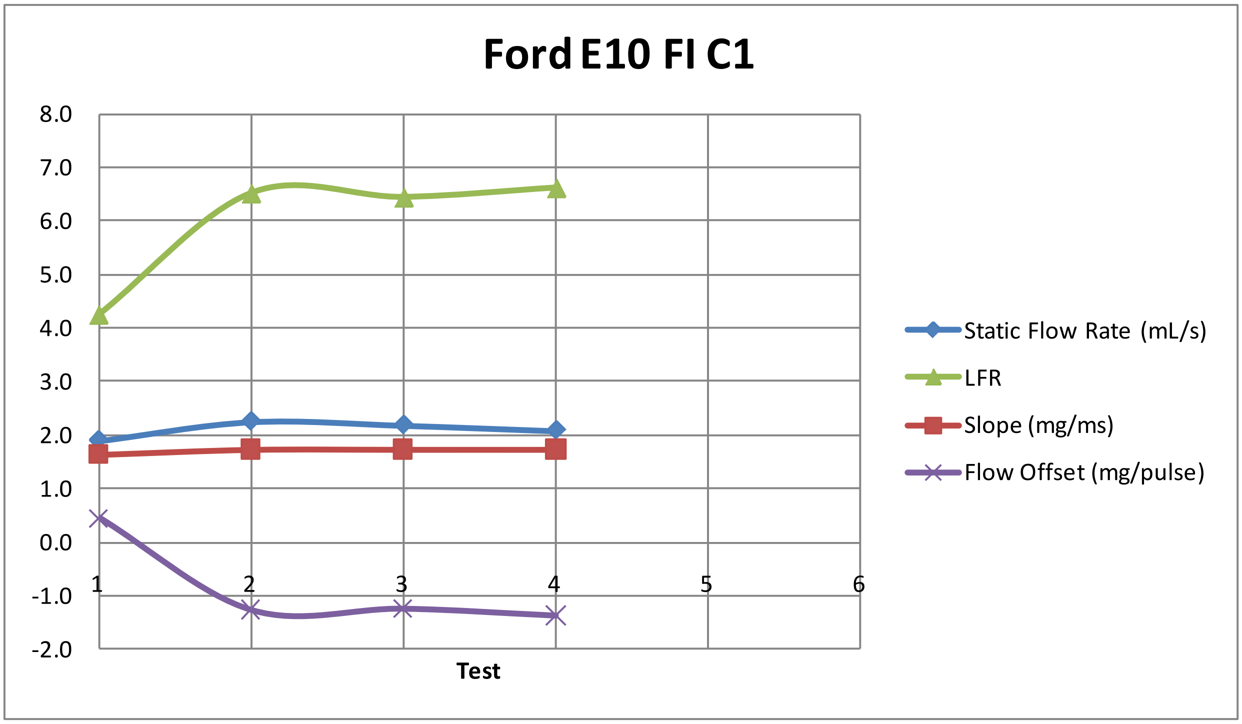

Figure A7: Significant parameters of Ford E10 fuel injector C1

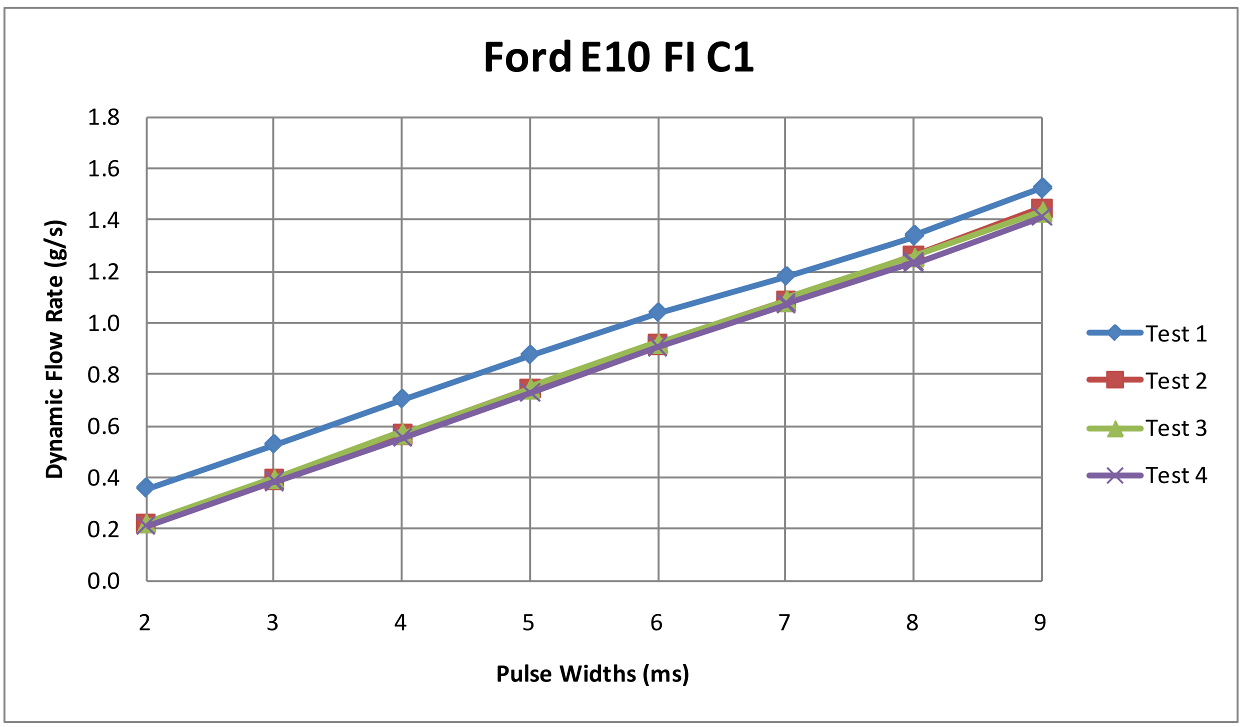

Figure A8: Dynamic flow rate of Ford E10 fuel injector C1

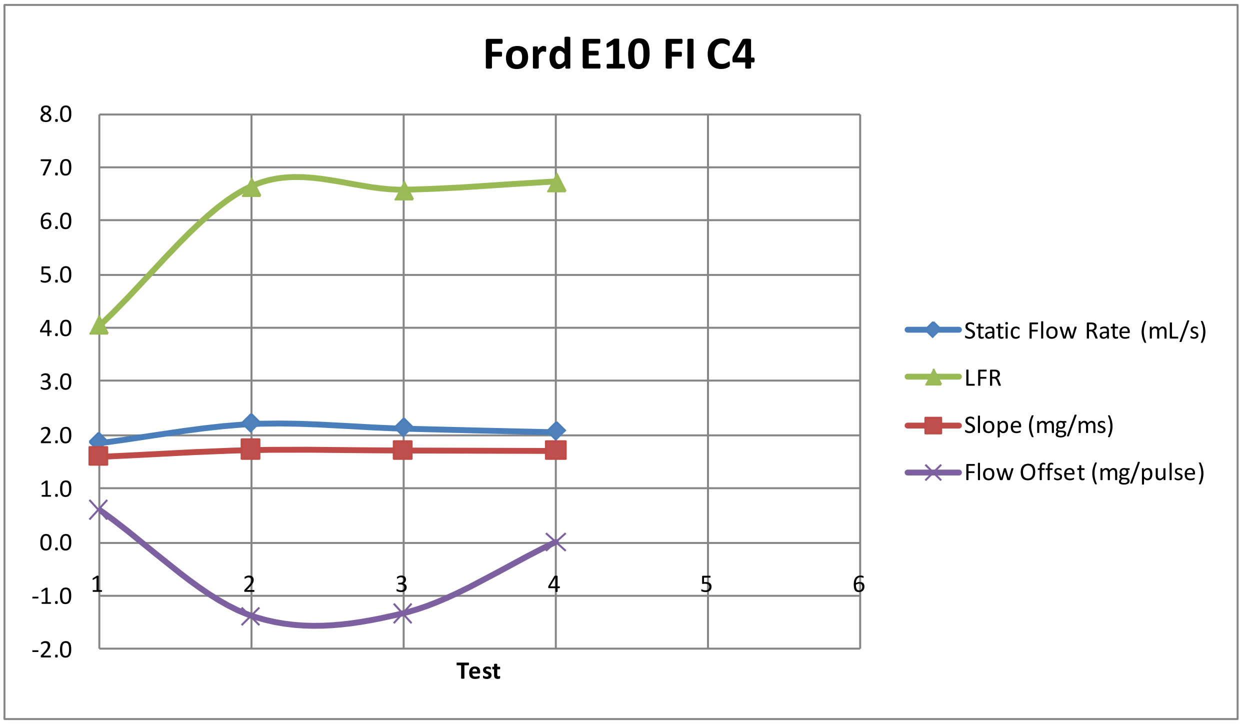

Figure A9: Significant parameters of Ford E10 fuel injector C4

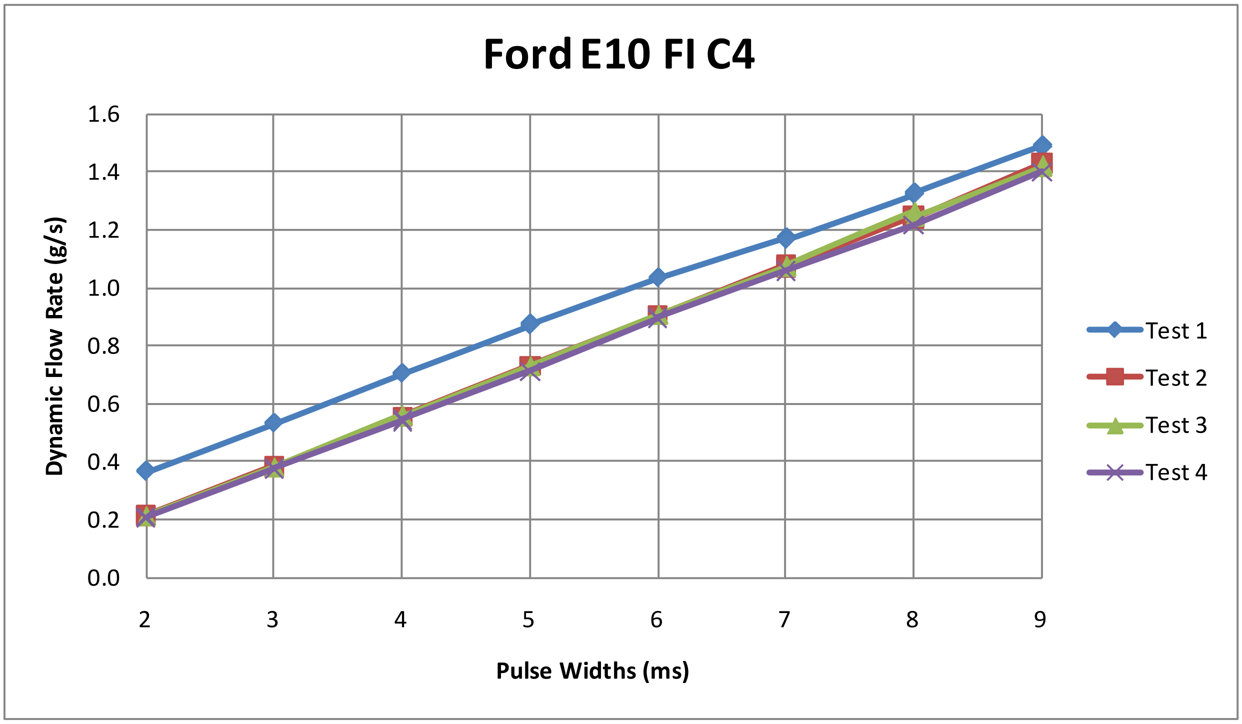

Figure A10: Dynamic flow rate of Ford E10 fuel injector C4

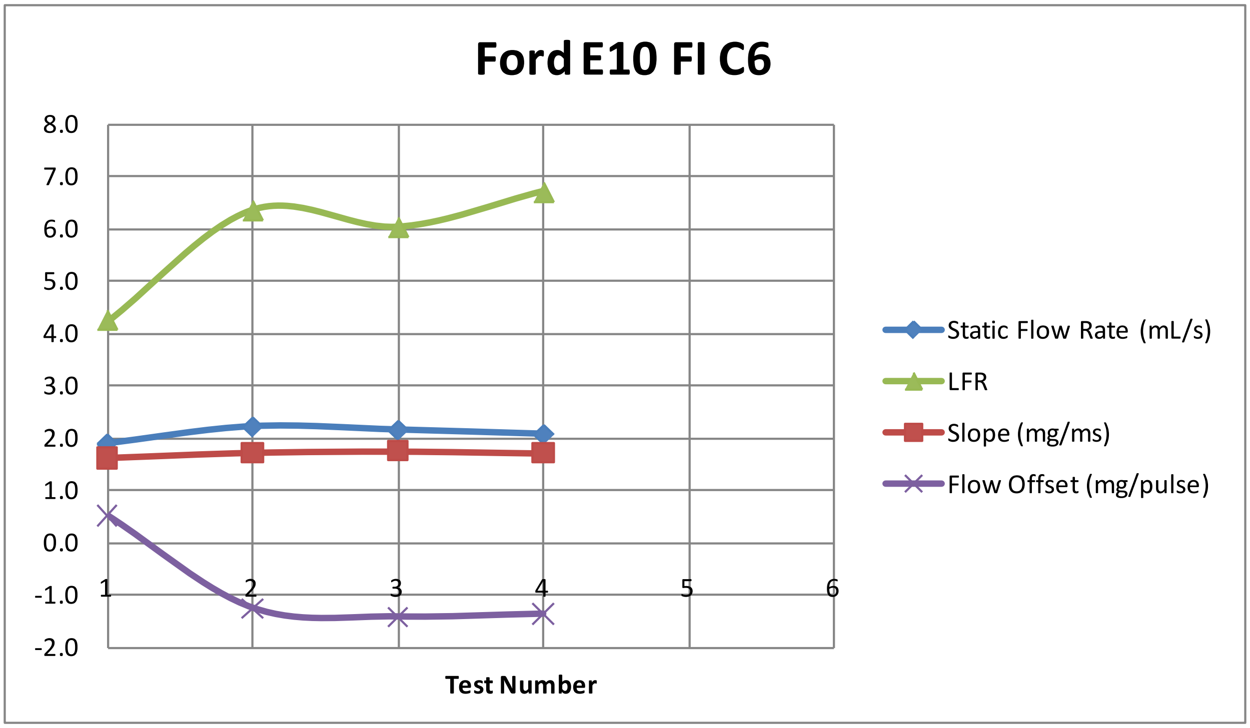

Figure A11: Significant parameters of Ford E10 fuel injector C6

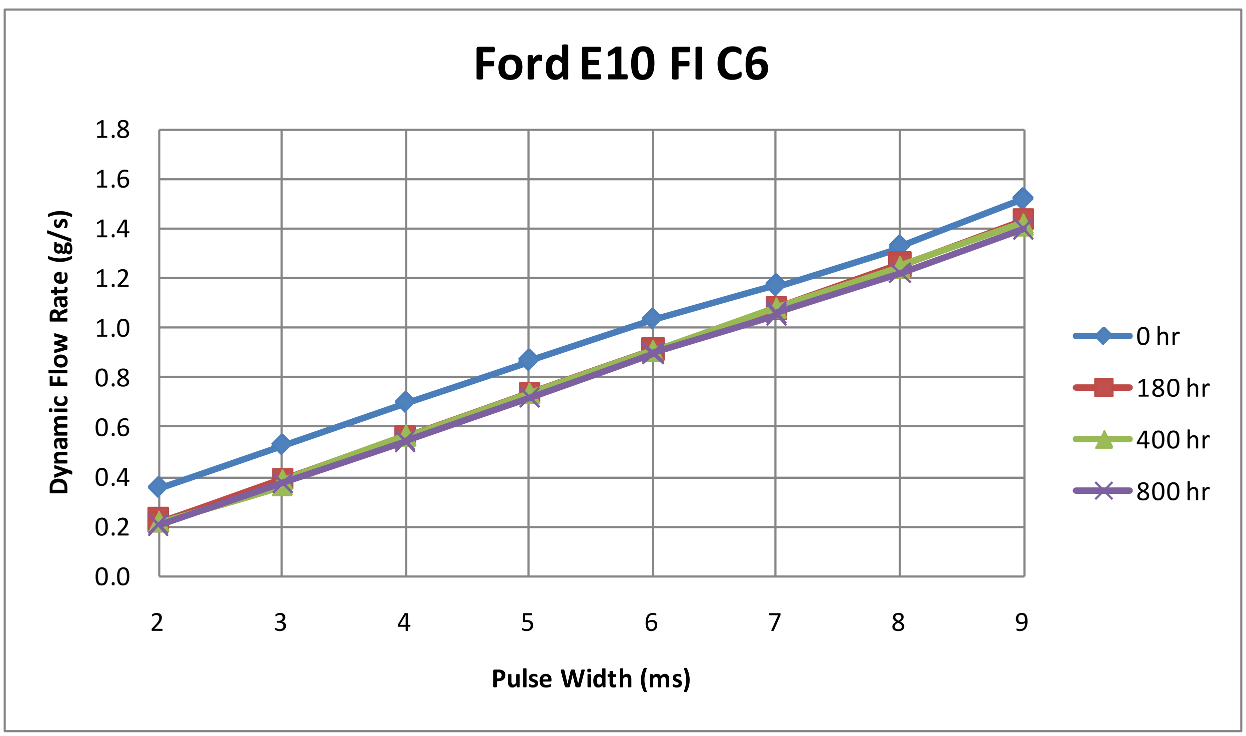

Figure A12: Dynamic flow rate of Ford E10 fuel injector C6

Table A3: Ford E17 Fuel Injector Data

Ford E17				
0	**hours**			
Injector	**Static Flow Rate**	**Slope**	**Flow Offset**	**LFR**
C5	2.217	1.776	0.388	4.220
C2	2.250	1.788	0.319	4.150
K5	2.117	2.106	0.975	1.502
H6	2.083	1.838	1.989	2.803
I5	2.217	1.801	0.159	4.299
I4	2.217	1.764	0.295	4.253
Average	**2.183**	**1.845**	**0.688**	**3.538**
Std. Dev.	**0.067**	**0.130**	**0.698**	**1.150**
162	**hours**			
Injector	**Static Flow Rate**	**Slope**	**Flow Offset**	**LFR**
C5	2.167	1.752	0.513	4.207
C2	2.167	1.757	0.413	4.130
K5	2.050	2.031	1.342	1.664
H6	2.050	1.944	2.053	2.627
I5	2.167	1.752	0.369	4.068
I4	2.150	1.748	0.363	4.163
Average	**2.125**	**1.831**	**0.842**	**3.476**
Std. Dev.	**0.058**	**0.125**	**0.702**	**1.076**
370.5	**hours**			
Injector	**Static Flow Rate**	**Slope**	**Flow Offset**	**LFR**
C5	2.200	1.749	0.539	4.041
C2	2.217	1.763	0.413	4.146
K5	2.067	2.040	1.341	2.173
H6	1.750	1.524	2.264	2.565
I5	2.200	1.775	0.338	4.185
I4	2.167	1.765	0.278	4.225
Average	**2.100**	**1.769**	**0.862**	**3.556**
Std. Dev.	**0.180**	**0.164**	**0.790**	**0.930**
700.5	**hours**			
Injector	**Static Flow Rate**	**Slope**	**Flow Offset**	**LFR**
C5	2.000	1.787	0.734	3.787
C2	2.100	1.803	0.661	3.864
K5	1.983	2.068	1.569	2.029
H6	1.950	1.922	2.431	2.507
I5	2.100	1.813	0.545	3.899
I4	2.100	1.783	0.572	3.920
Average	**2.039**	**1.863**	**1.085**	**3.334**
Std. Dev.	**0.069**	**0.113**	**0.762**	**0.841**
841.5	**hours**			

Ford E17				
0	**hours**			
Injector	**Static Flow Rate**	**Slope**	**Flow Offset**	**LFR**
Injector	**Static Flow Rate**	**Slope**	**Flow Offset**	**LFR**
C5	2.117	1.790	0.798	3.807
C2	2.117	1.786	0.799	3.839
K5	2.017	2.085	1.557	2.369
H6	1.983	1.953	2.389	2.548
I5	2.133	1.797	0.659	3.909
I4	2.083	1.790	0.608	3.918
Average	**2.075**	**1.867**	**1.135**	**3.398**
Std. Dev.	**0.061**	**0.125**	**0.705**	**0.731**
1,101	**hours**			
Injector	**Static Flow Rate**	**Slope**	**Flow Offset**	**LFR**
C5	2.067	1.793	0.741	3.696
C2	2.083	1.791	0.697	3.750
K5	2.133	1.873	2.288	2.614
H6	1.950	1.949	2.269	2.540
I5	2.067	1.795	0.562	3.821
I4	2.067	1.791	0.522	3.884
Average	**2.061**	**1.832**	**1.180**	**3.384**
Std. Dev.	**0.060**	**0.066**	**0.855**	**0.629**

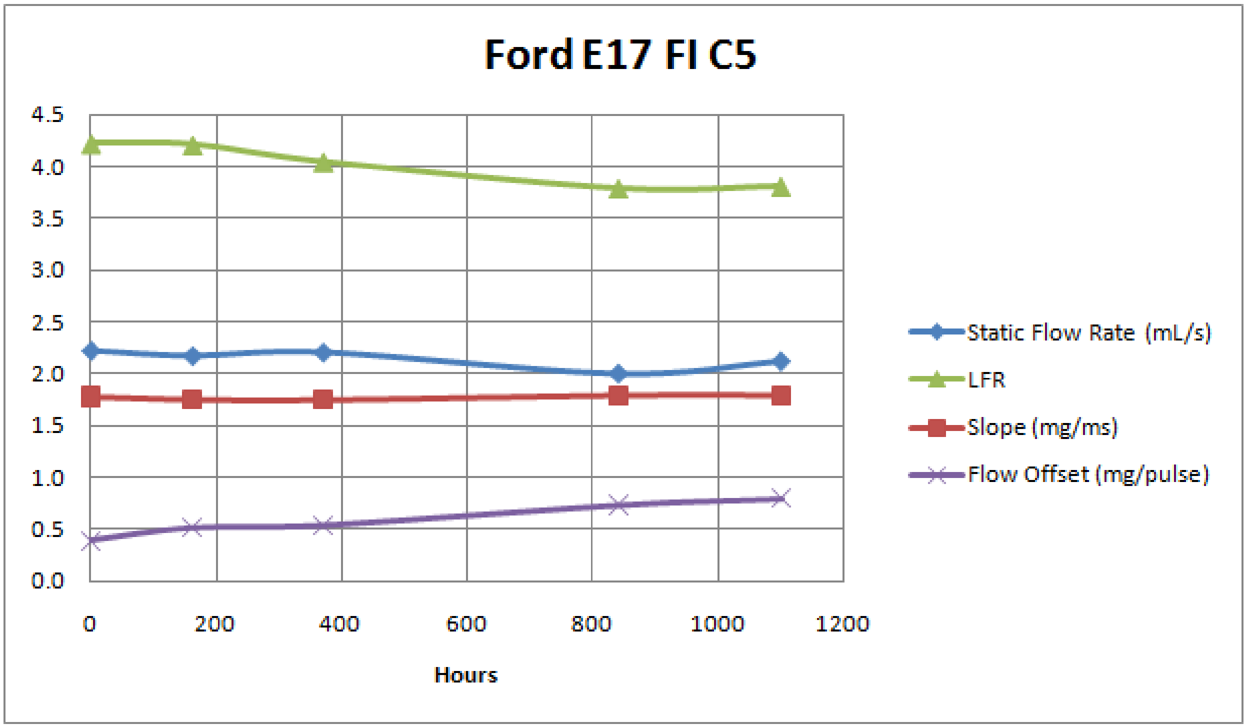

Figure A13: Significant parameters of Ford E17 fuel injector C5

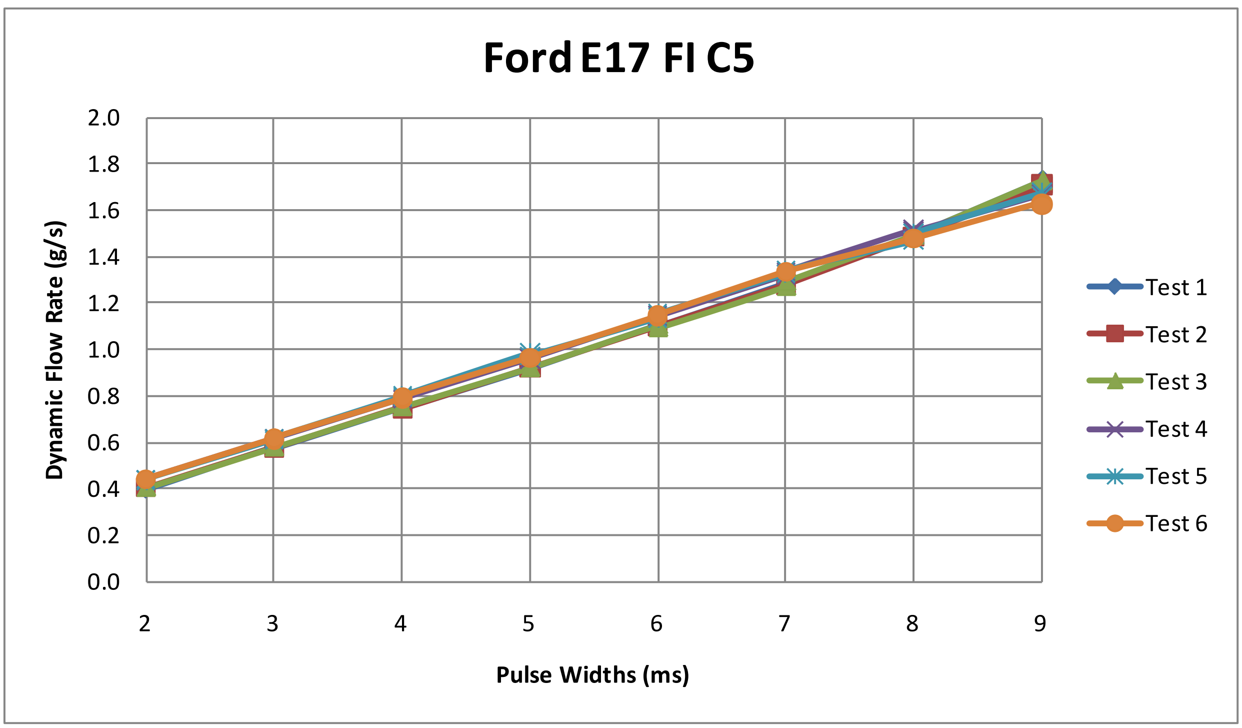

Figure A14: Dynamic flow rate of Ford E17 fuel injector C5

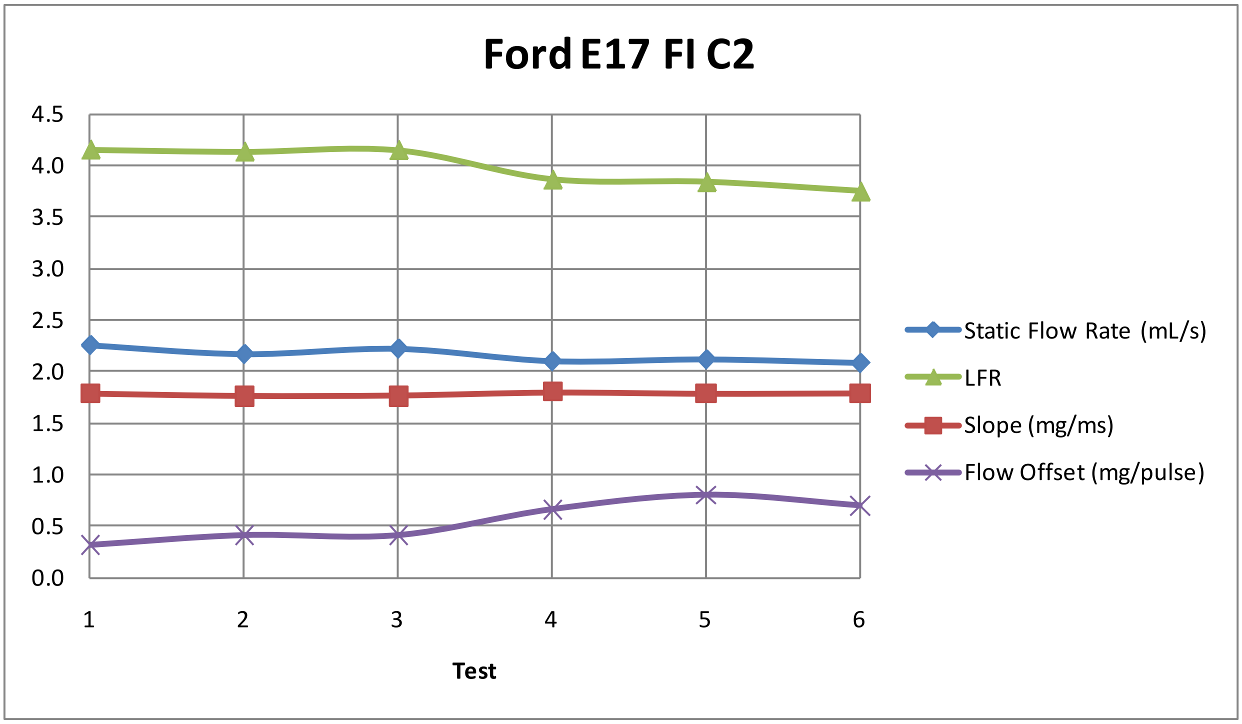

Figure A15: Significant parameters of Ford E17 fuel injector C2

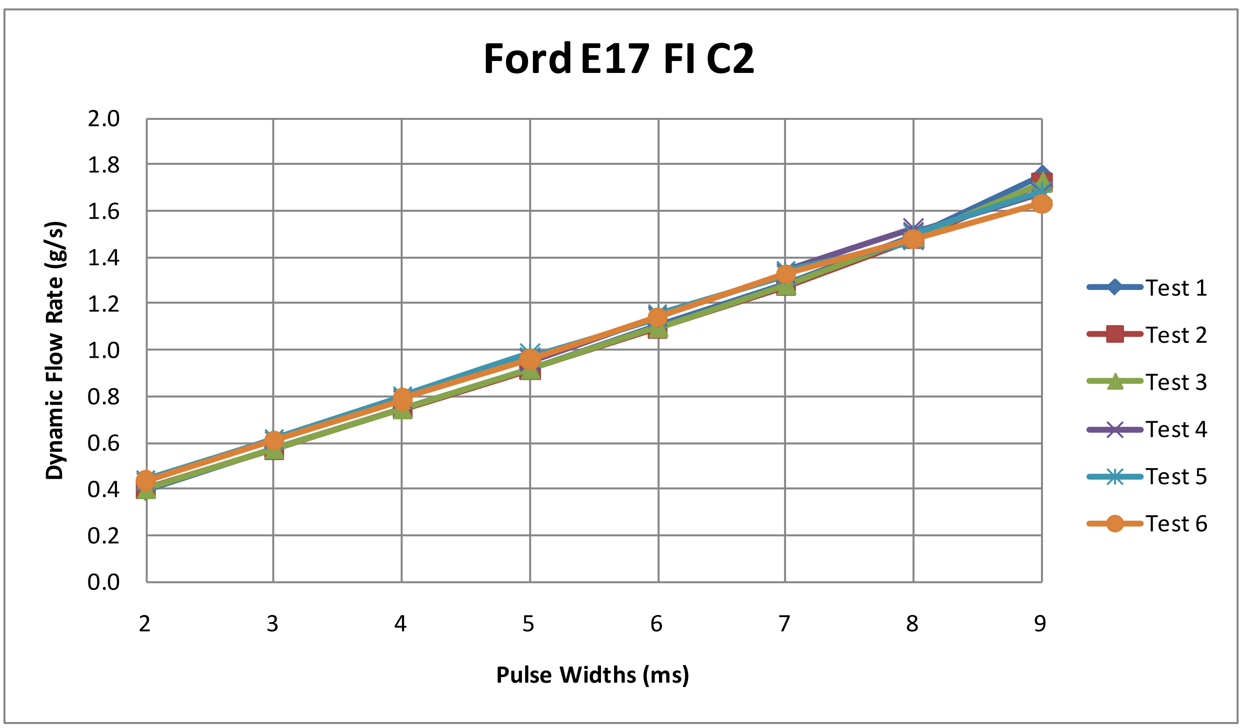

Figure A16: Dynamic flow rate of Ford E17 fuel injector C2

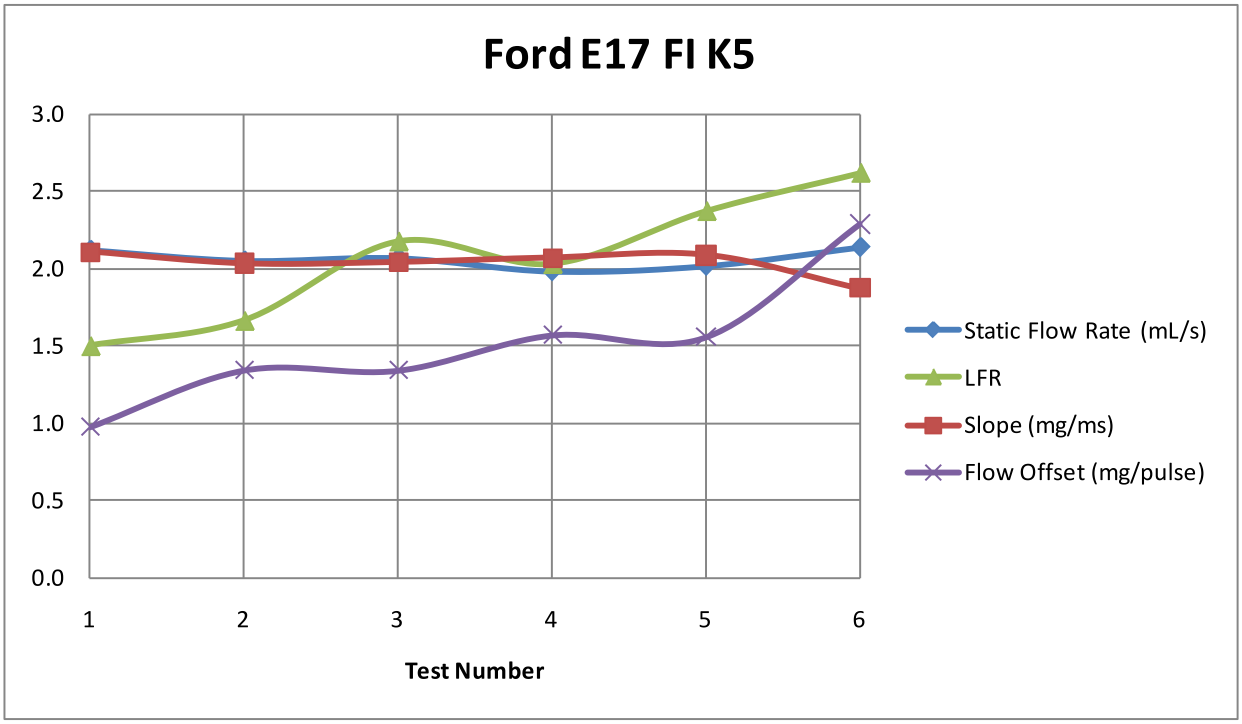

Figure A17: Significant parameters of Ford E17 fuel injector K5

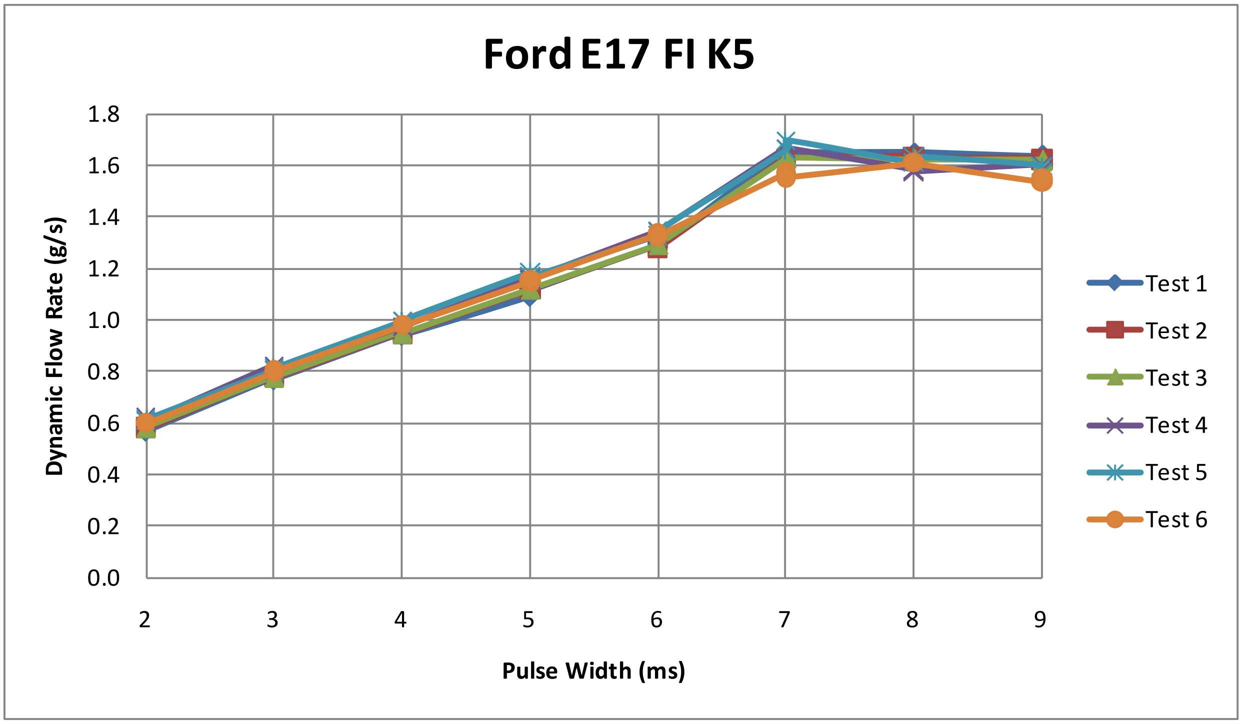

Figure A18: Dynamic flow rate of Ford E17 fuel injector K5

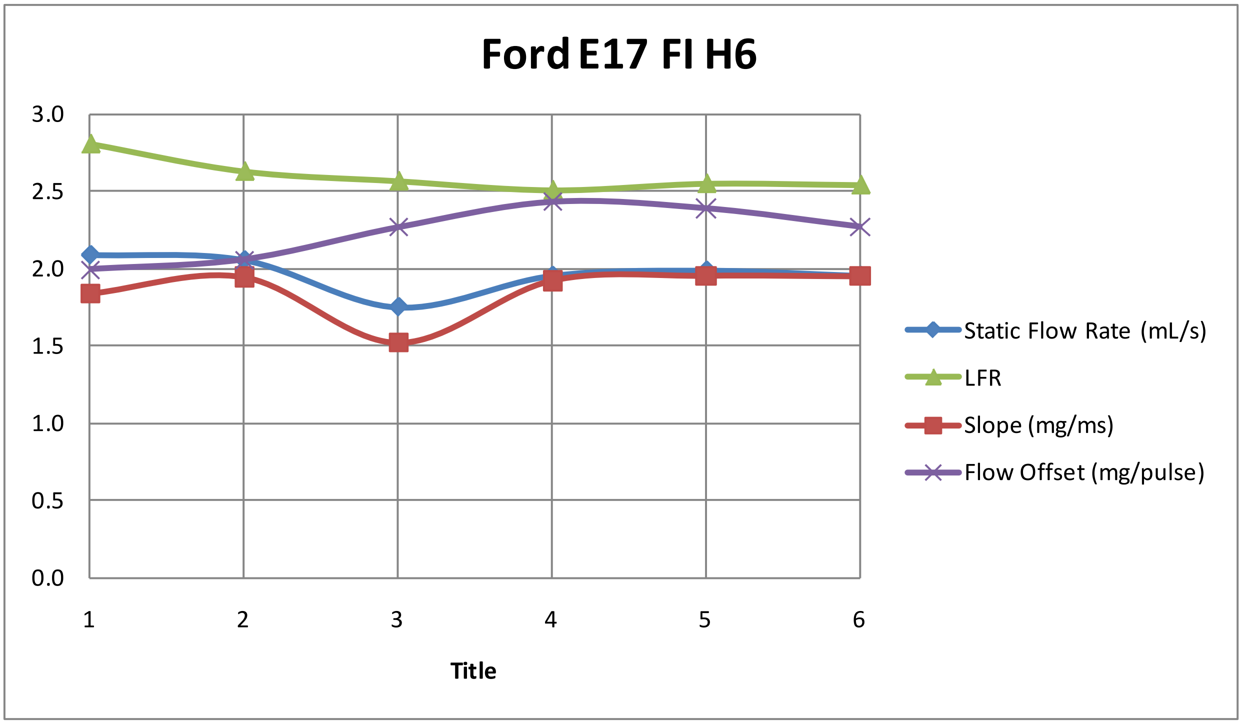

Figure A19: Significant parameters of Ford E17 fuel injector H6

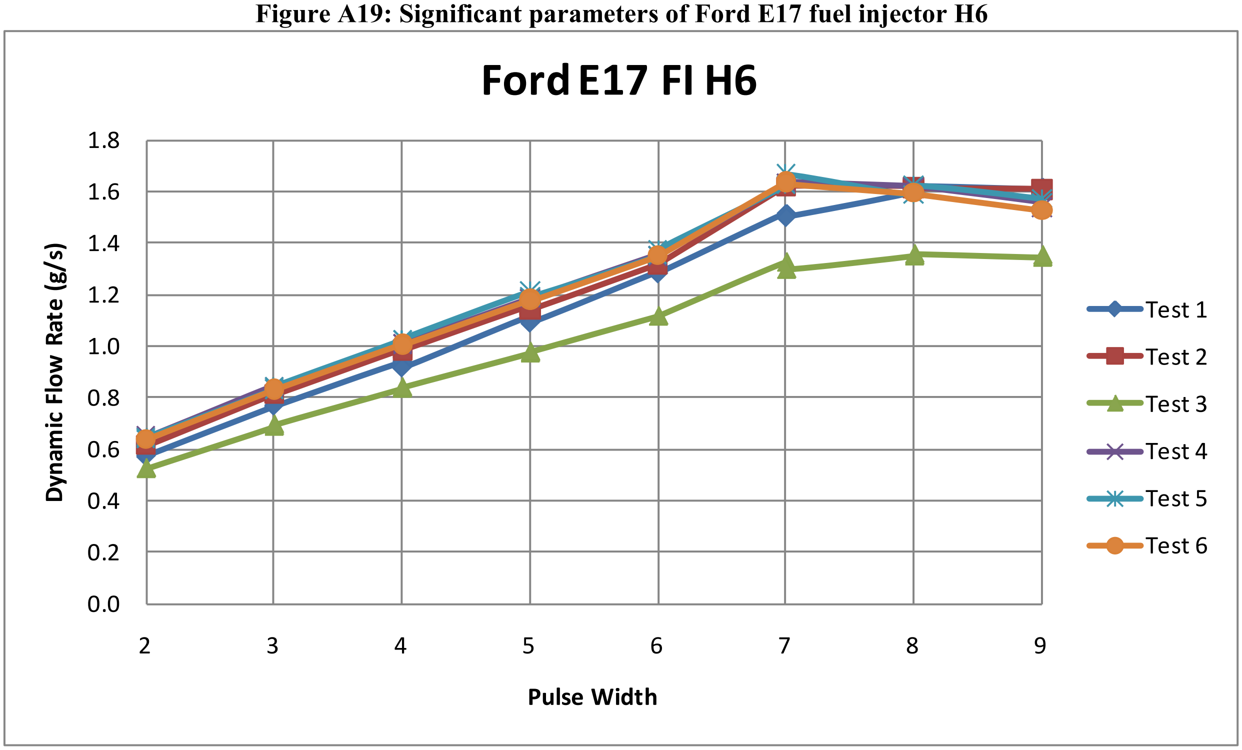

Figure A20: Dynamic flow rate of Ford E17 fuel injector H6

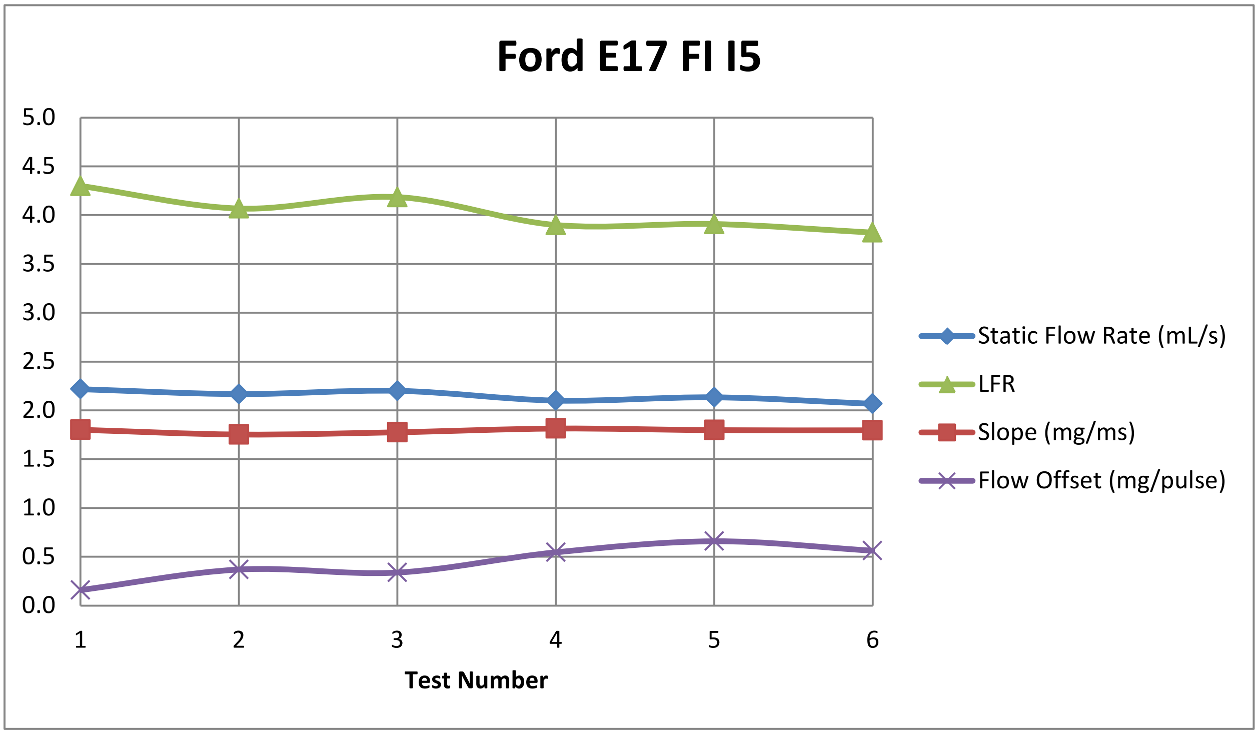

Figure A21: Significant parameters of Ford E17 fuel injector I5

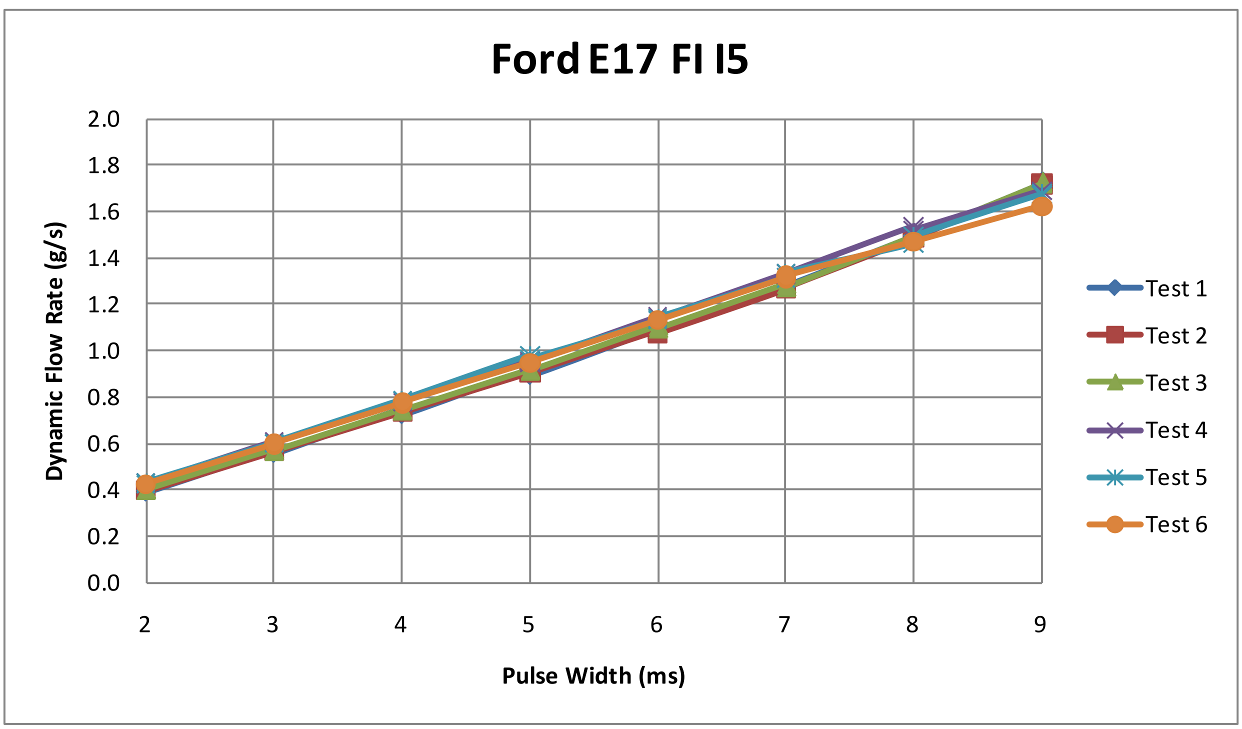

Figure A22: Dynamic flow rate of Ford E17 fuel injector I5

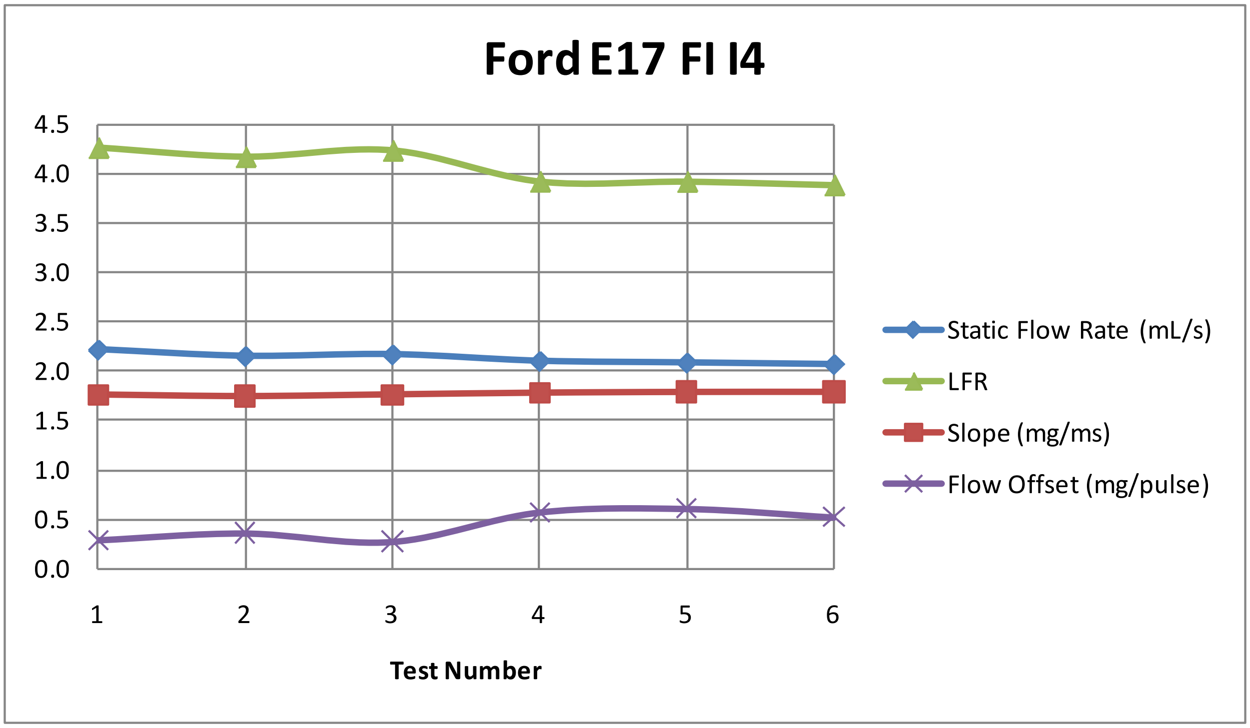

Figure A23: Significant parameters of Ford E17 fuel injector I4

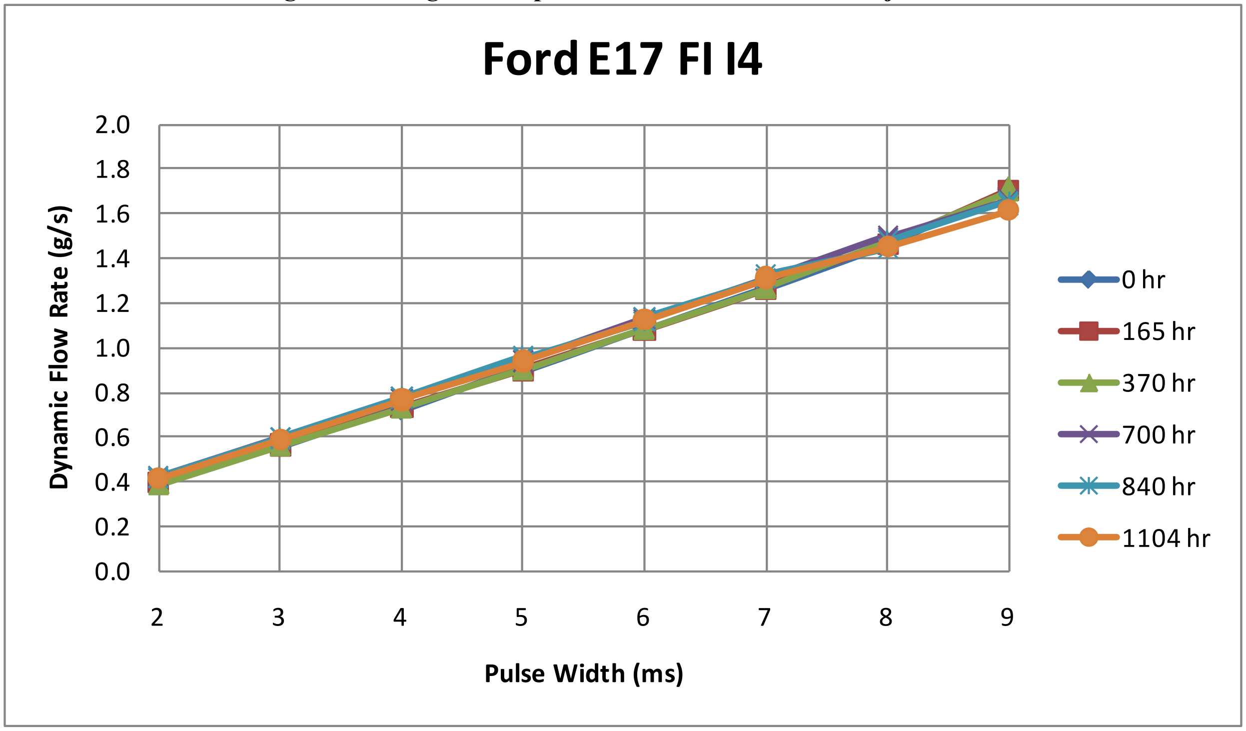

Figure A24: Dynamic flow rate of Ford E17 fuel injector I4

Table A 4: GM E10 Fuel Injector Data

GM E10				
0	**hours**			
Injector	**Static Flow Rate**	**Slope**	**Flow Offset**	**LFR**
A5	2.483	2.272	1.788	2.798
D2	2.550	2.360	1.309	2.850
D1	2.367	2.098	1.999	2.724
A4	2.533	2.287	1.566	2.816
A1	2.533	2.353	1.780	2.872
A3	2.517	2.284	2.061	2.964
Average	**2.497**	**2.276**	**1.750**	**2.837**
Std. Dev.	**0.068**	**0.095**	**0.279**	**0.080**
177.8	**hours**			
Injector	**Static Flow Rate**	**Slope**	**Flow Offset**	**LFR**
A5	2.683	2.470	2.191	3.148
D2	2.733	2.519	1.945	3.229
D1	2.517	2.308	2.094	3.257
A4	2.683	2.469	2.141	3.195
A1	2.750	2.482	2.778	3.003
A3	2.717	2.421	2.658	3.061
Average	**2.681**	**2.445**	**2.301**	**3.149**
Std. Dev.	**0.085**	**0.074**	**0.335**	**0.099**
379.5	**hours**			
Injector	**Static Flow Rate**	**Slope**	**Flow Offset**	**LFR**
A5	2.650	2.345	2.382	3.148
D2	2.500	2.340	2.228	3.153
D1	2.483	2.163	2.462	3.602
A4	2.683	2.394	2.205	3.232
A1	2.717	2.367	2.828	3.044
A3	2.667	2.380	2.377	3.082
Average	**2.617**	**2.332**	**2.414**	**3.210**
Std. Dev.	**0.099**	**0.085**	**0.226**	**0.203**
813.8	**hours**			
Injector	**Static Flow Rate**	**Slope**	**Flow Offset**	**LFR**
A5	3.050	2.271	2.589	2.903
D2	3.083	2.359	2.027	3.218
D1	3.117	2.151	2.355	2.853
A4	3.100	2.392	2.090	3.322
A1	3.100	2.365	2.751	3.059
A3	3.050	2.351	2.452	3.093
Average	**3.083**	**2.315**	**2.377**	**3.075**
Std. Dev.	**0.028**	**0.090**	**0.281**	**0.180**
1,669	**hours**			
Injector	**Static Flow Rate**	**Slope**	**Flow Offset**	**LFR**

GM E10				
0	**hours**			
Injector	**Static Flow Rate**	**Slope**	**Flow Offset**	**LFR**
A5	2.717	2.439	-0.786	4.187
D2	2.750	2.516	-1.092	4.711
D1	2.550	2.291	-0.710	4.886
A4	2.750	2.471	-0.941	5.130
A1	2.750	2.488	-0.565	3.658
A3	2.733	2.459	-0.516	4.904
Average	**2.708**	**2.444**	**-0.768**	**4.579**
Std. Dev.	**0.079**	**0.079**	**0.221**	**0.552**

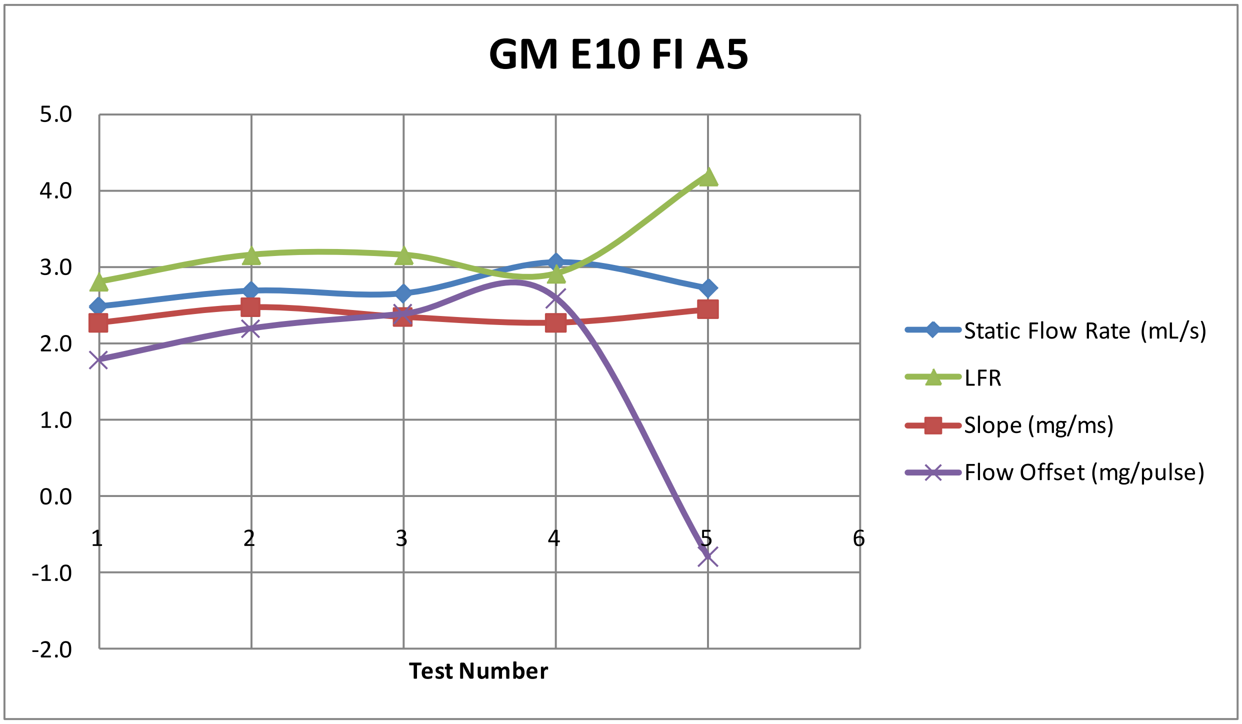

Figure A25: Significant parameters of GM E10 fuel injector A5

Figure A26: Dynamic flow rate of GM E10 fuel injector A5

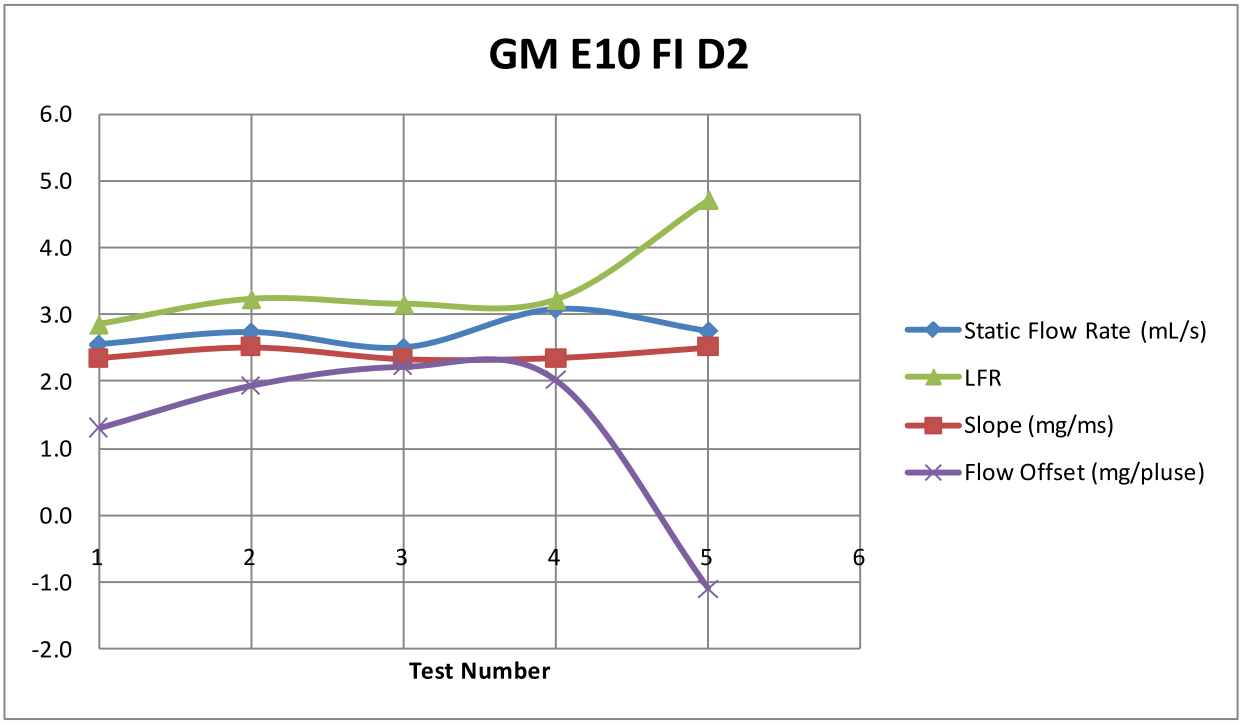

Figure A27: Significant parameters of GM E10 fuel injector D2

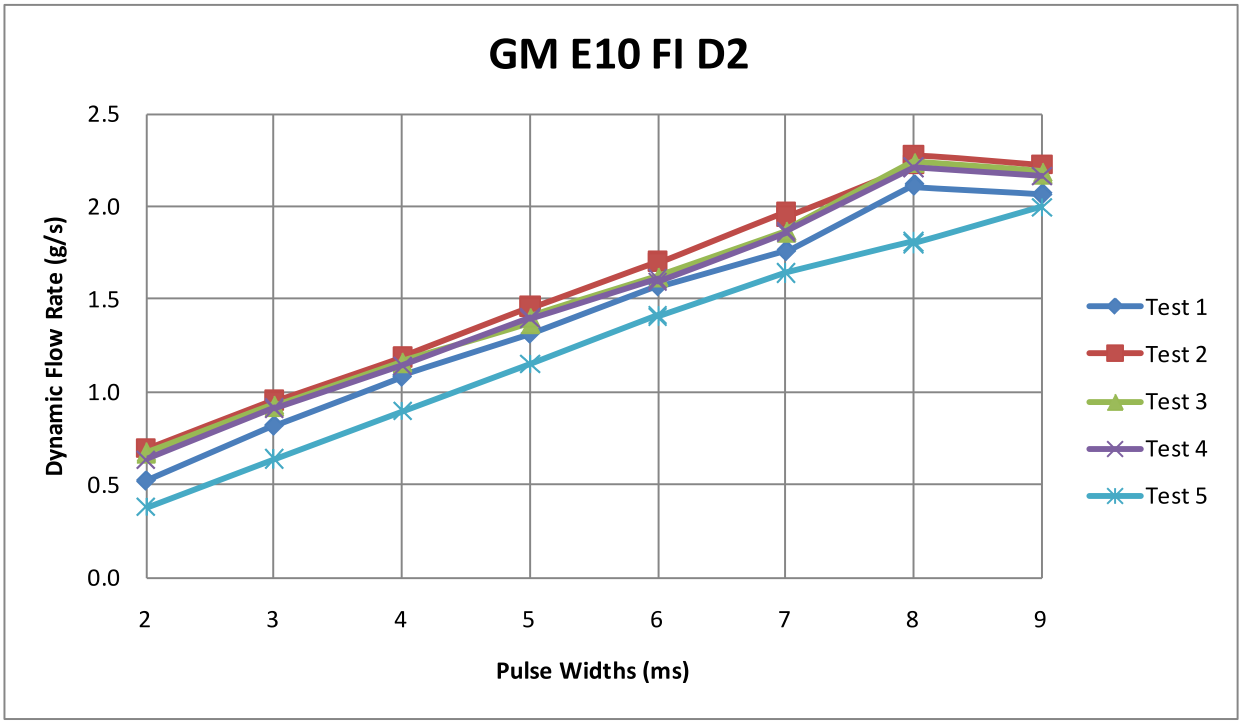

Figure A28: Dynamic flow rate of GM E10 fuel injector D2

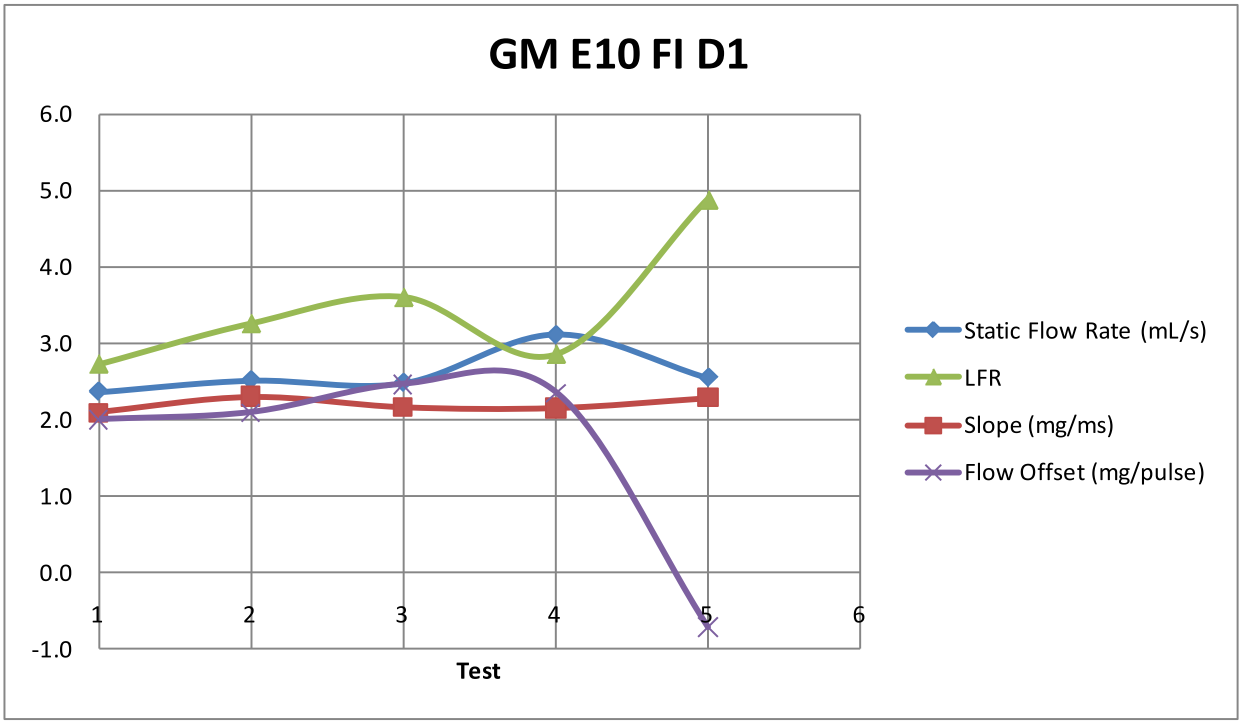

Figure A29: Significant parameters of GM E10 fuel injector D1

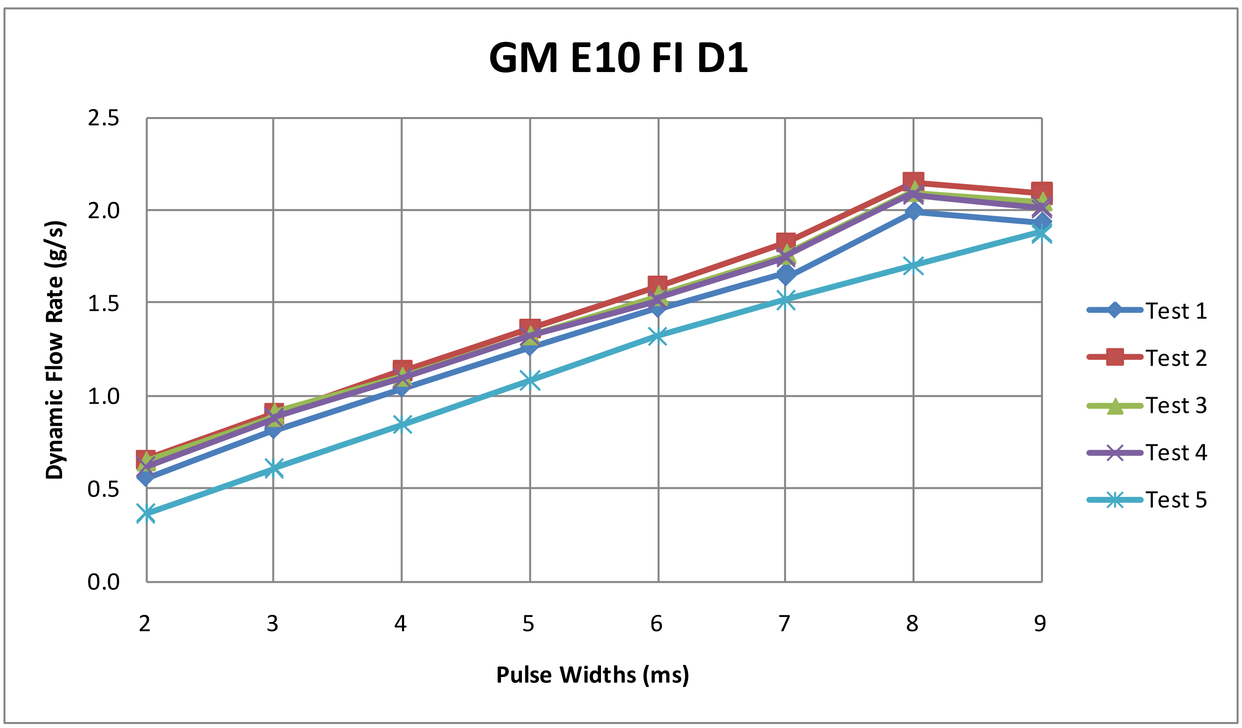

Figure A30: Dynamic flow rate of GM E10 fuel injector D1

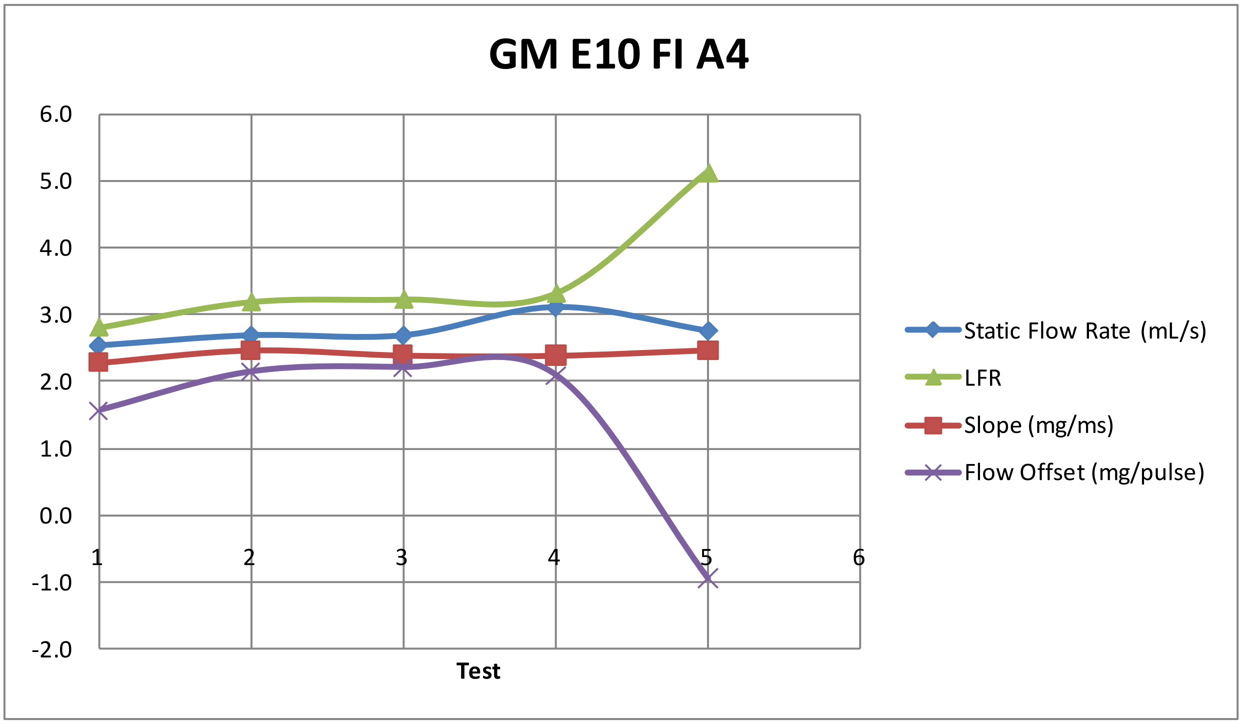

Figure A31: Significant parameters of GM E10 fuel injector A4

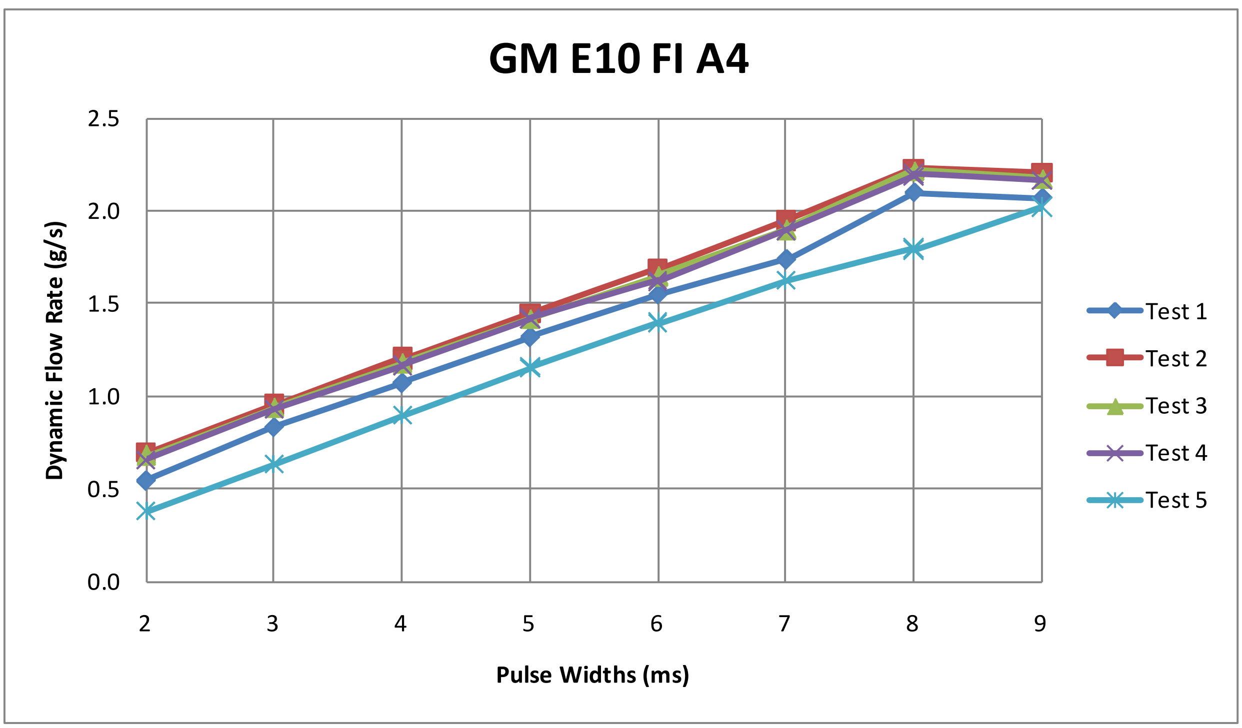

Figure A32: Dynamic flow rate of GM E10 fuel injector A4

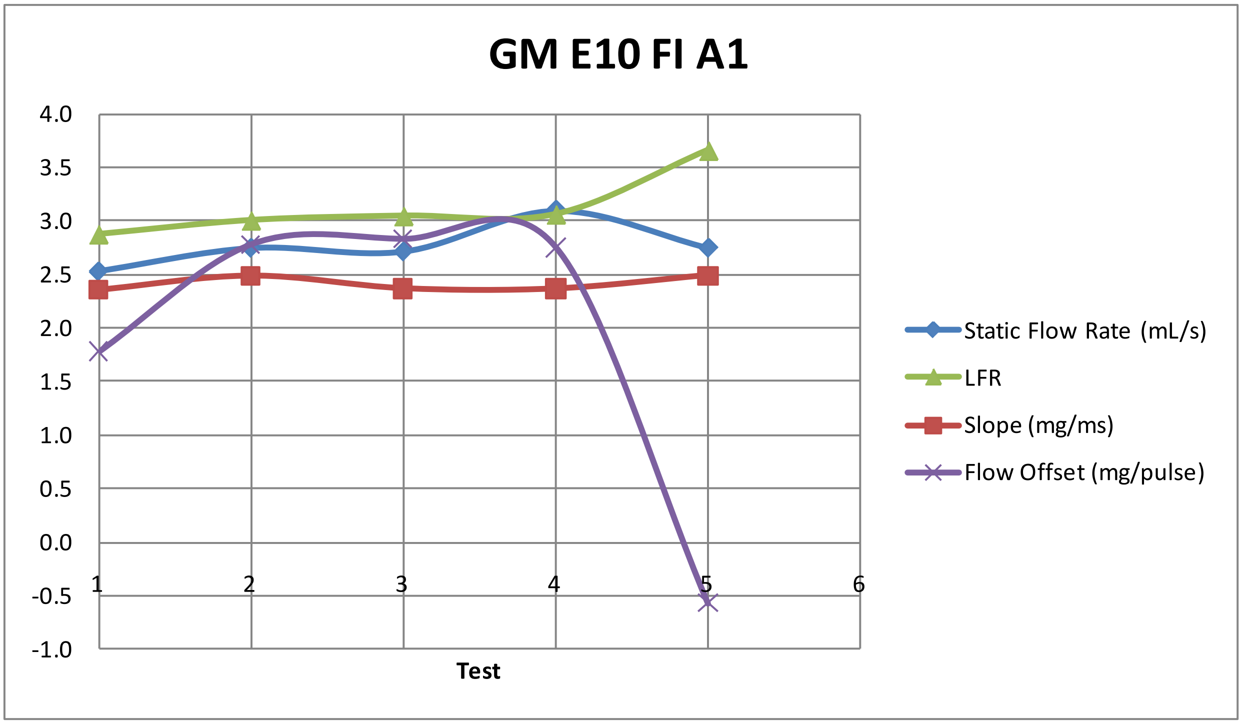

Figure A33: Significant parameters of GM E10 fuel injector A1

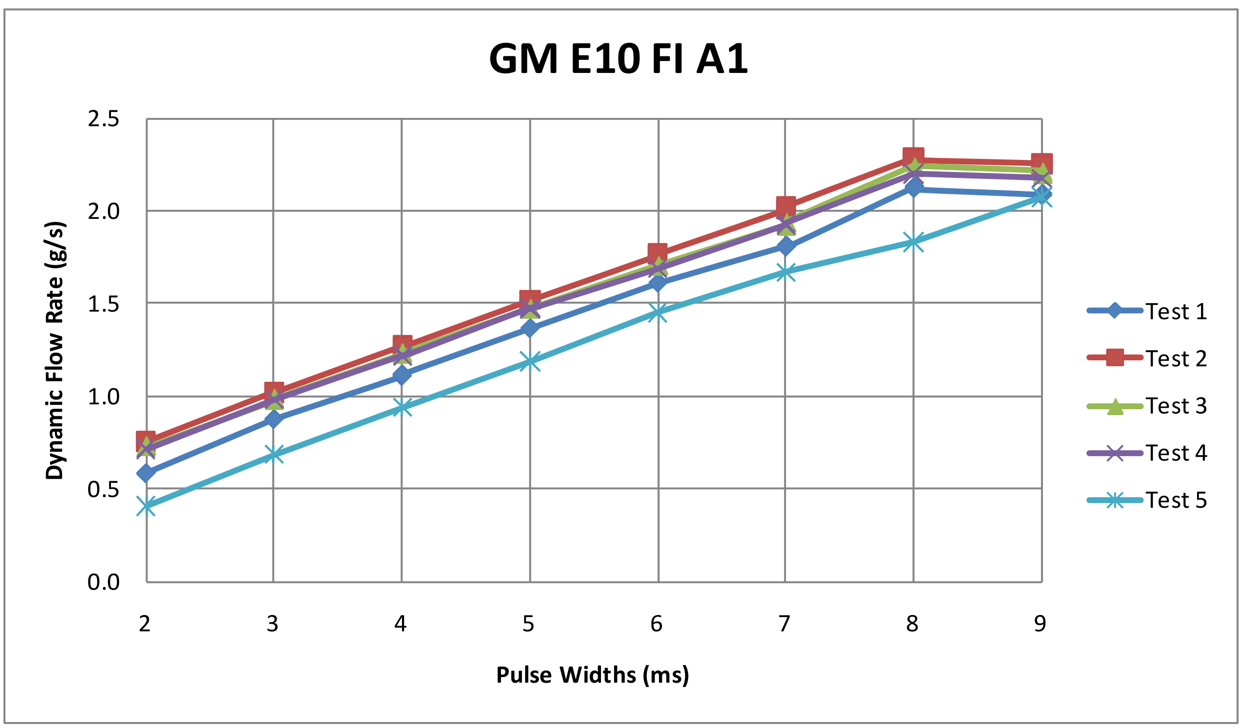

Figure A34: Dynamic flow rate of GM E10 fuel injector A1

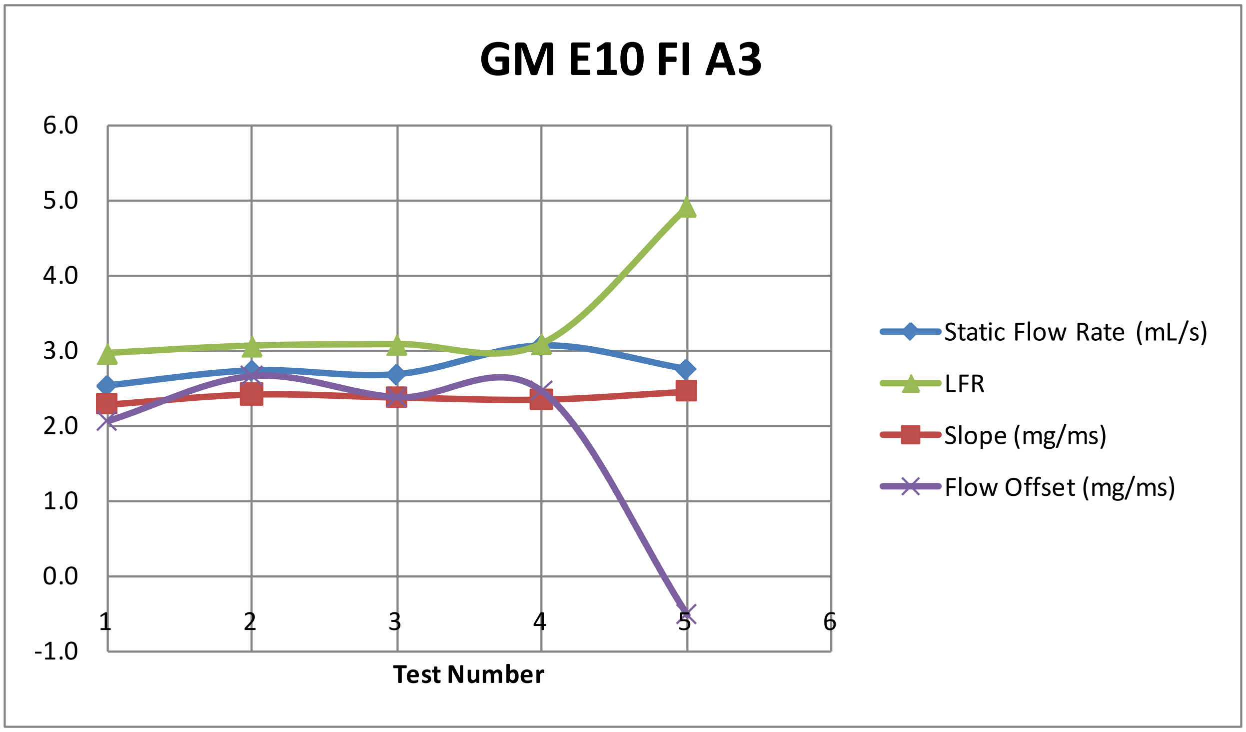

Figure A35: Significant parameters of GM E10 fuel injector A3

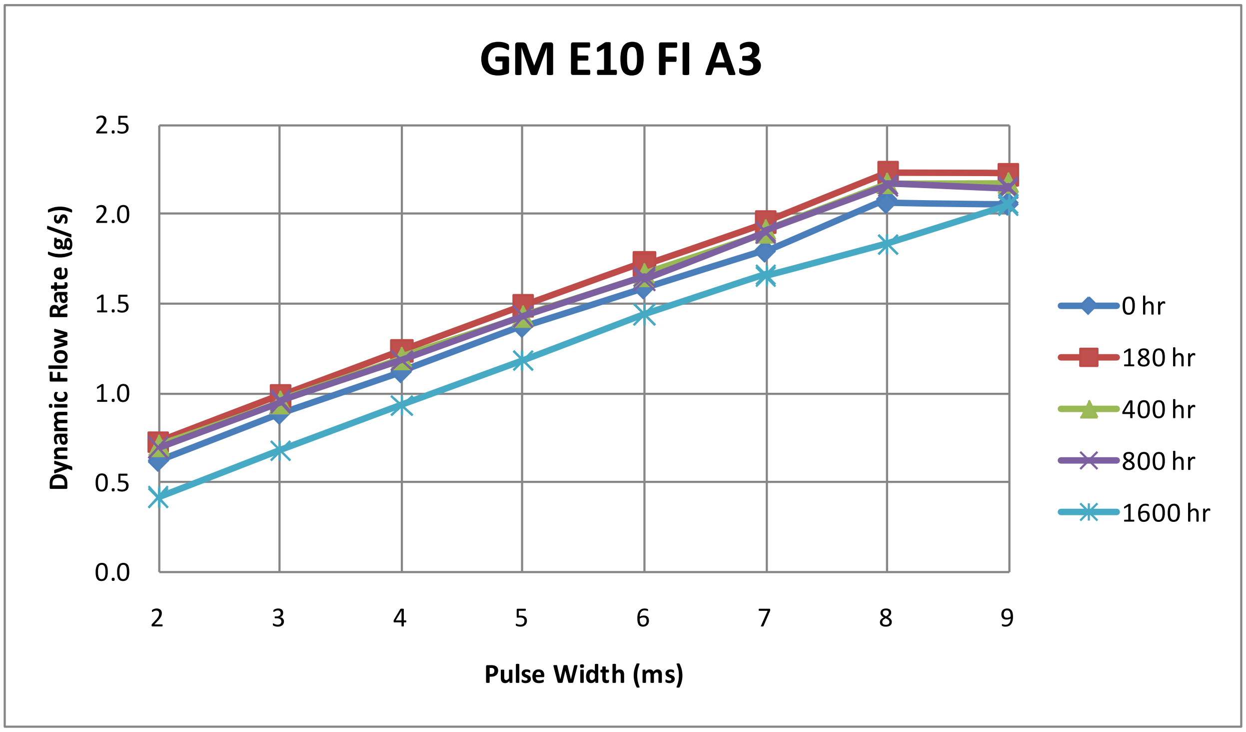

Figure A36: Dynamic flow rate of GM E10 fuel injector A3

Table A5: GM E17 Fuel Injector Data

GM E17				
0	**hours**			
Injector	**Static Flow Rate**	**Slope**	**Flow Offset**	**LFR**
B1	2.850	2.396	2.185	3.158
B3	2.683	2.284	2.367	3.082
B2	2.767	2.319	2.203	3.156
B4	2.750	2.301	2.270	3.098
B5	2.733	2.322	2.423	2.991
B6	2.833	2.446	2.318	3.090
Average	**2.769**	**2.345**	**2.295**	**3.096**
Std. Dev.	**0.063**	**0.063**	**0.093**	**0.061**
163.5	**hours**			
Injector	**Static Flow Rate**	**Slope**	**Flow Offset**	**LFR**
B1	2.583	2.258	2.046	2.583
B3	2.483	2.170	1.911	3.157
B2	2.533	2.210	1.996	3.143
B4	2.517	2.176	2.039	3.091
B5	2.550	2.261	2.234	3.169
B6	2.650	2.337	2.315	3.117
Average	**2.553**	**2.235**	**2.090**	**3.043**
Std. Dev.	**0.058**	**0.063**	**0.153**	**0.227**
375	**hours**			
Injector	**Static Flow Rate**	**Slope**	**Flow Offset**	**LFR**
B1	2.633	2.327	2.743	2.908
B3	2.667	2.233	2.617	2.909
B2	2.717	2.279	2.739	2.875
B4	2.700	2.277	2.565	2.895
B5	2.717	2.287	3.032	2.761
B6	2.817	2.369	3.179	2.733
Average	**2.708**	**2.295**	**2.812**	**2.847**
Std. Dev.	**0.062**	**0.047**	**0.242**	**0.079**
708.8	**hours**			
Injector	**Static Flow Rate**	**Slope**	**Flow Offset**	**LFR**
B1	2.517	2.139	3.010	2.811
B3	2.367	2.022	2.909	2.828
B2	2.450	2.056	3.133	2.802
B4	2.400	2.050	2.949	2.800
B5	2.350	2.073	3.347	2.670
B6	2.533	2.126	3.654	2.618
Average	**2.436**	**2.078**	**3.167**	**2.755**
Std. Dev.	**0.077**	**0.046**	**0.286**	**0.088**

GM E17				
0	**hours**			
Injector	**Static Flow Rate**	**Slope**	**Flow Offset**	**LFR**
851.3	**hours**			
Injector	**Static Flow Rate**	**Slope**	**Flow Offset**	**LFR**
B1	2.483	2.093	3.313	2.709
B3	2.350	1.986	3.231	2.631
B2	2.417	2.010	3.403	2.579
B4	2.383	2.015	3.297	2.646
B5	2.417	2.003	3.846	2.395
B6	2.483	2.055	4.023	2.285
Average	**2.422**	**2.027**	**3.519**	**2.541**
Std. Dev.	**0.053**	**0.040**	**0.331**	**0.165**
1,113	**hours**			
Injector	**Static Flow Rate**	**Slope**	**Flow Offset**	**LFR**
B1	2.500	2.054	3.509	2.749
B3	2.383	1.961	3.404	2.688
B2	2.450	1.994	3.560	2.679
B4	2.417	2.016	3.374	2.717
B5	2.450	2.015	3.893	2.506
B6	2.517	2.062	4.099	2.335
Average	**2.453**	**2.017**	**3.640**	**2.612**
Std. Dev.	**0.050**	**0.038**	**0.292**	**0.160**

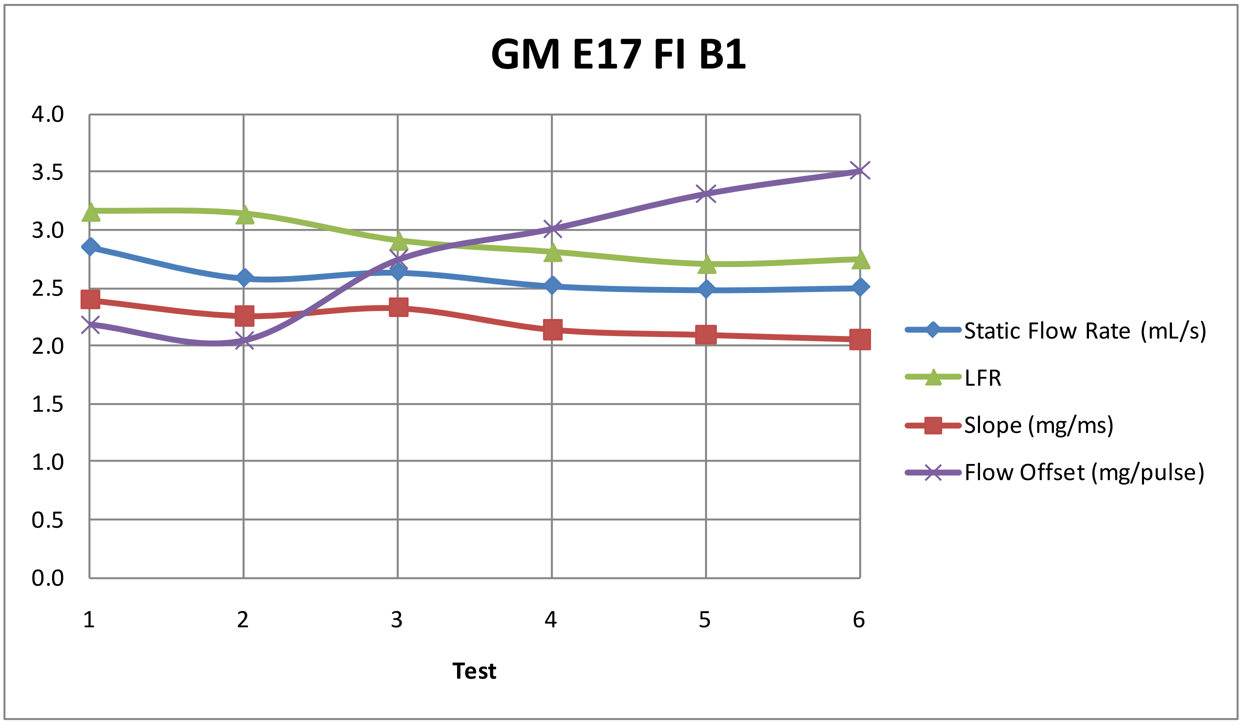

Figure A37: Significant parameters of GM E17 fuel injector B1

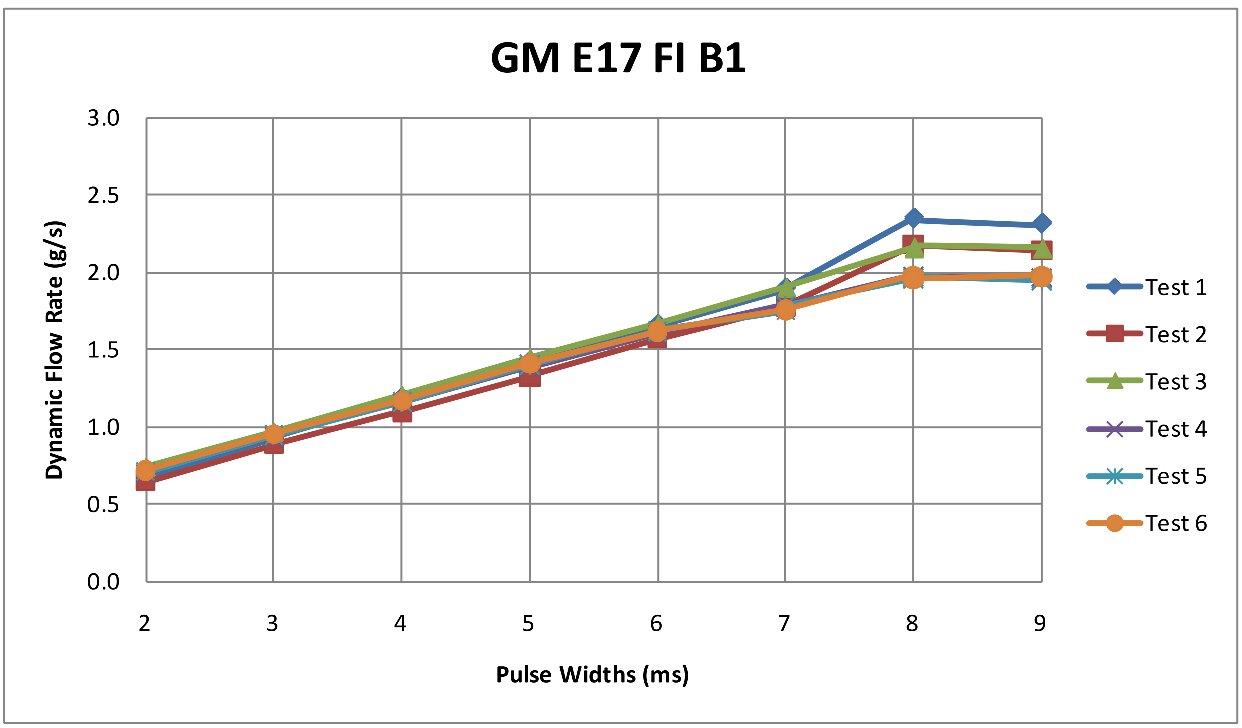

Figure A38: Dynamic flow rate of GM E17 fuel injector B1

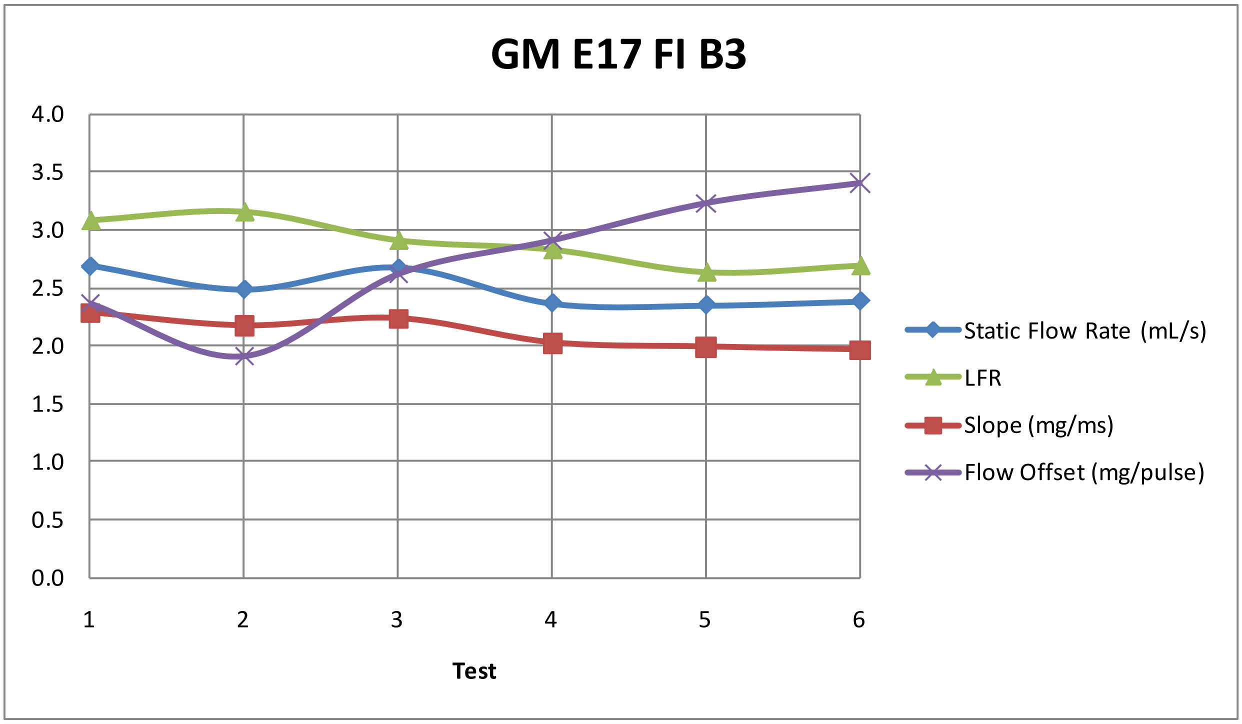

Figure A39: Significant parameters of GM E17 fuel injector B3

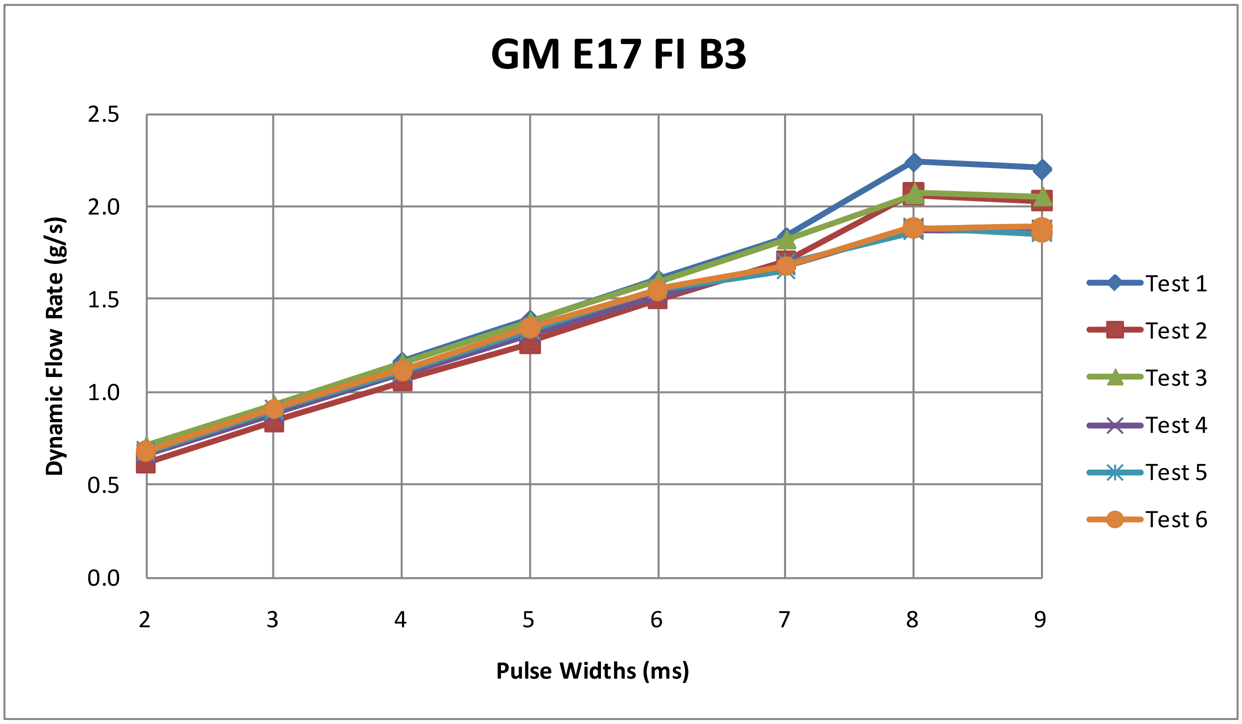

Figure A40: Dynamic flow rate of GM E17 fuel injector B3

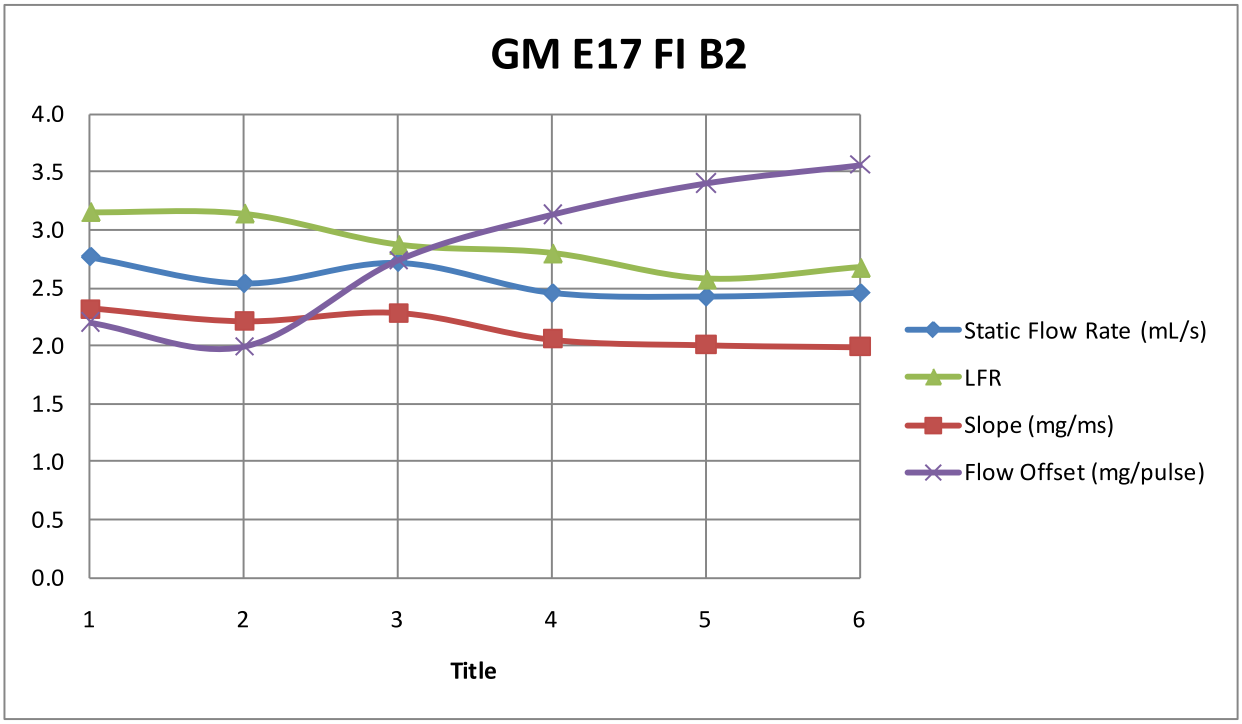

Figure A41: Significant parameters of GM E17 fuel injector B2

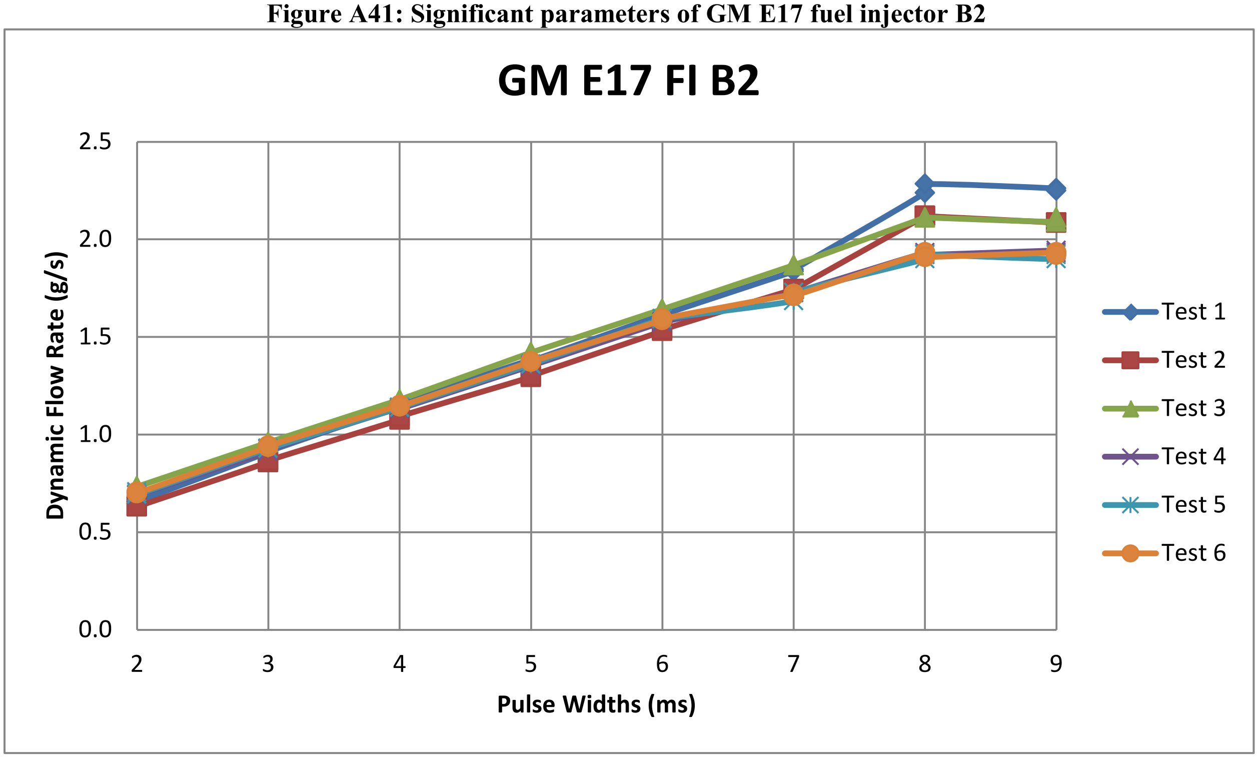

Figure A42: Dynamic flow rate of GM E17 fuel injector B2

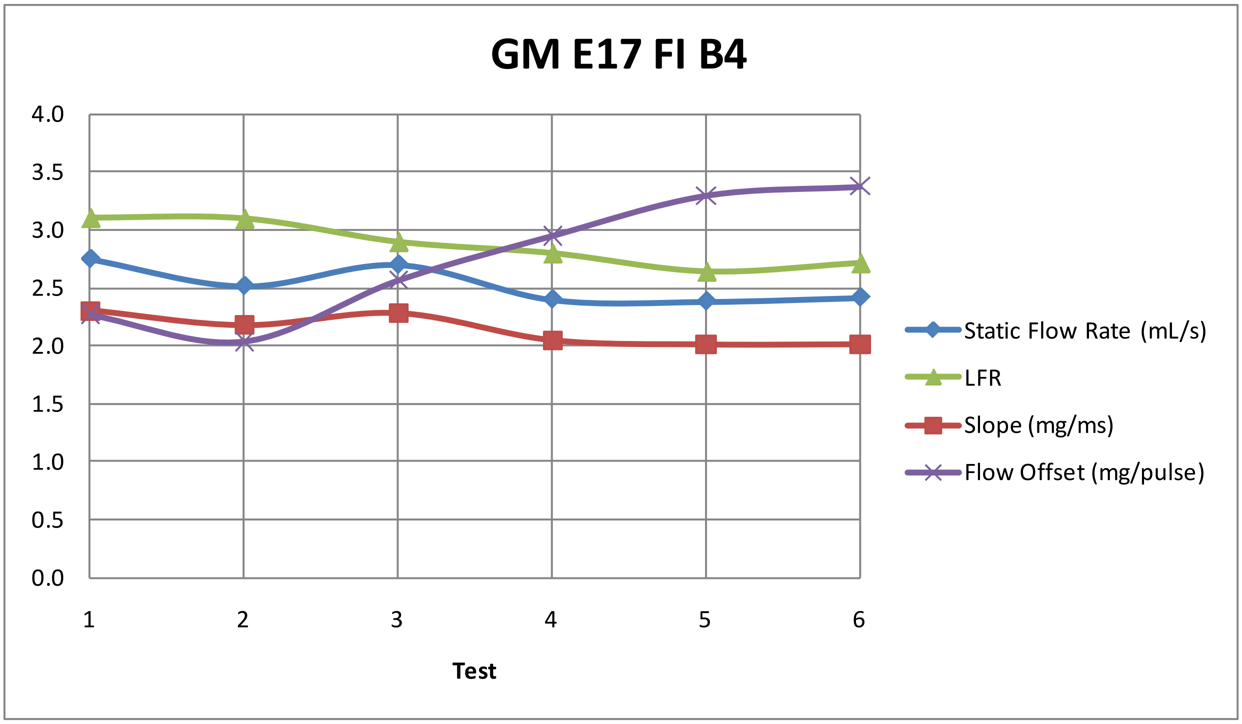

Figure A43: Significant parameters of GM E17 fuel injector B4

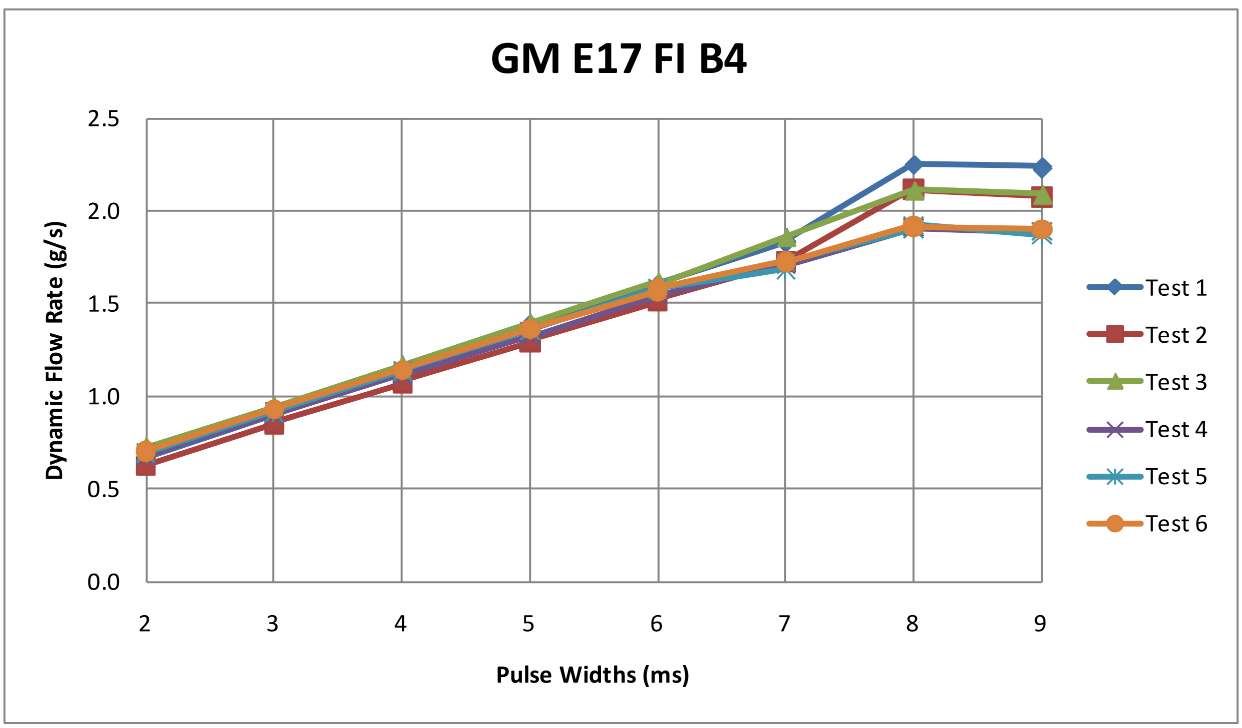

Figure A44: Dynamic flow rate of GM E17 fuel injector B4

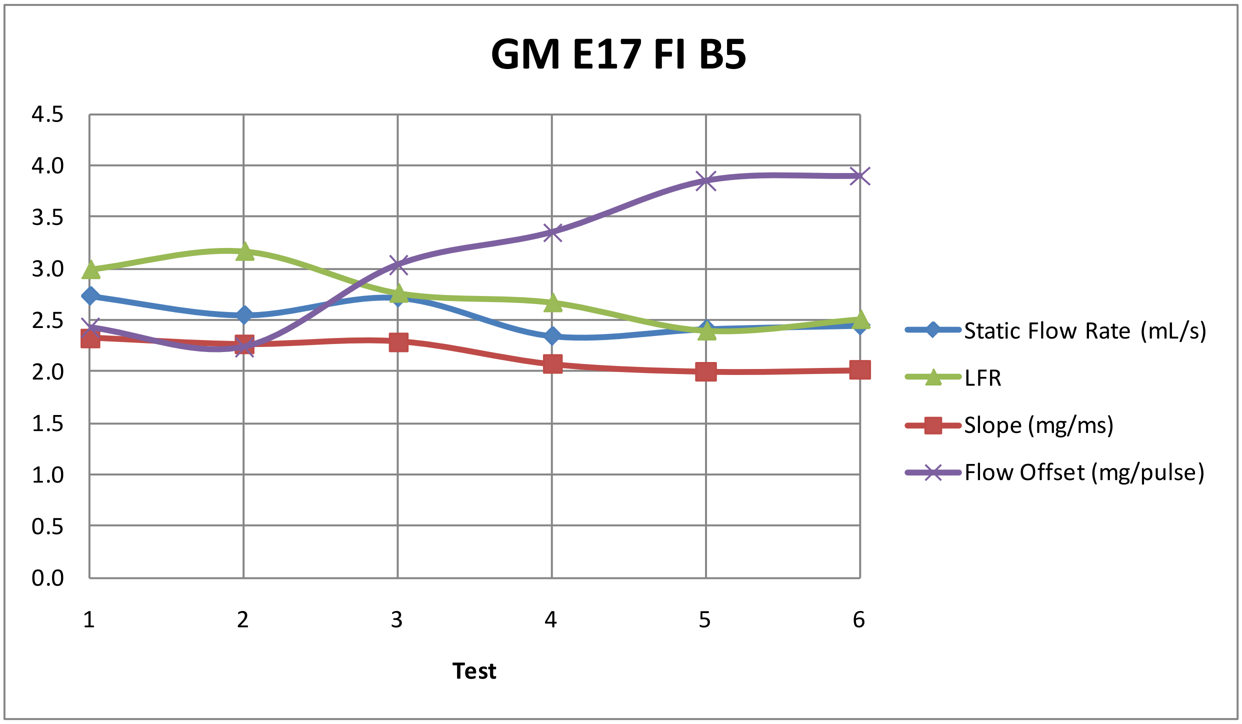

Figure A45: Significant parameters of GM E17 fuel injector B5

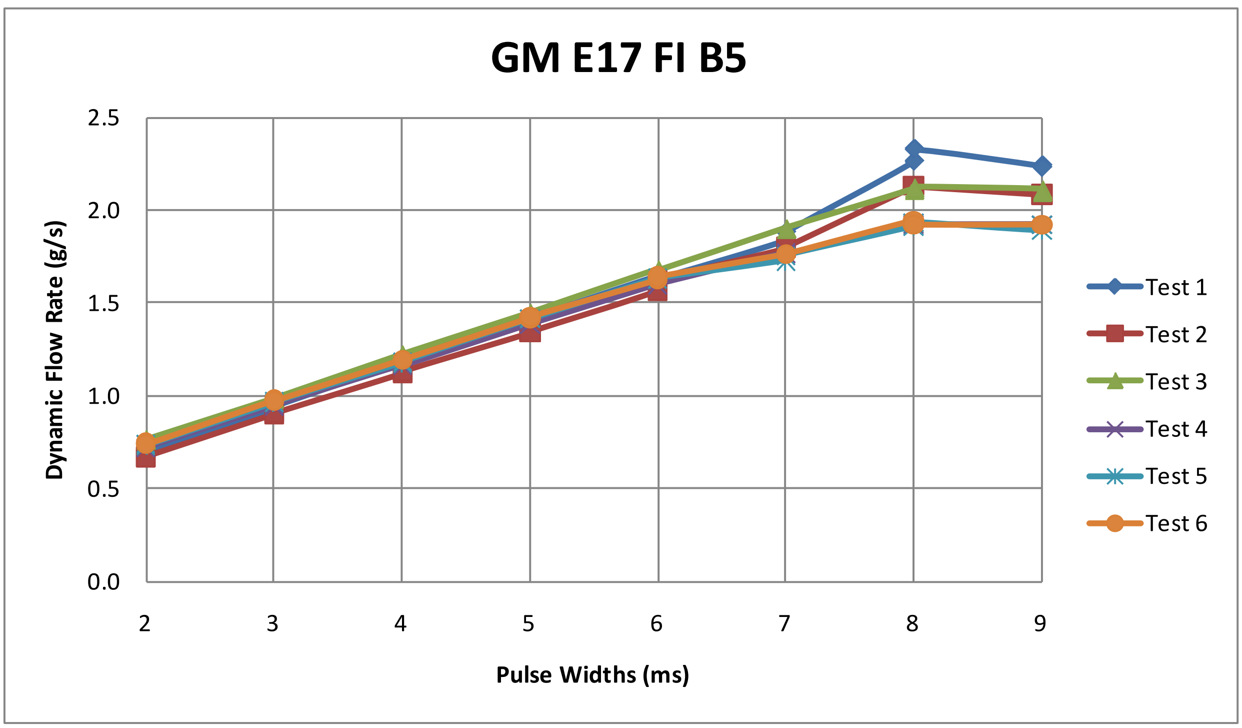

Figure A46: Dynamic flow rate of GM E17 fuel injector B5

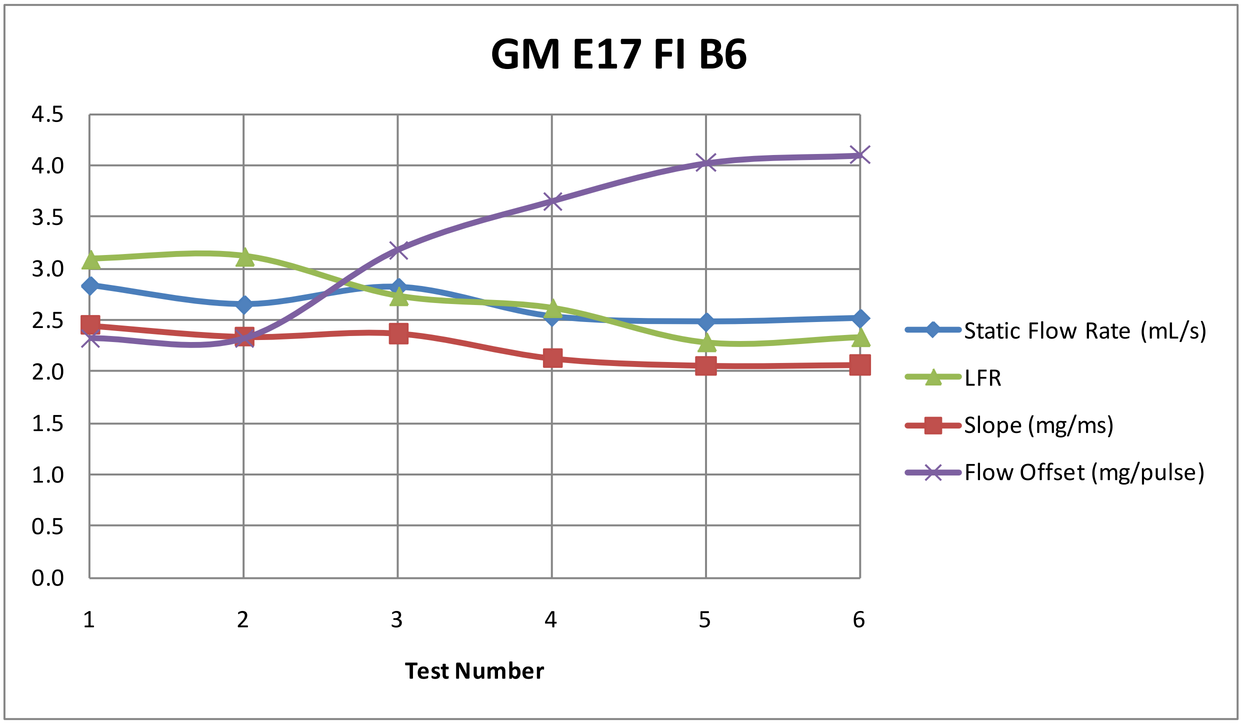

Figure A47: Significant parameters of GM E17 fuel injector B6

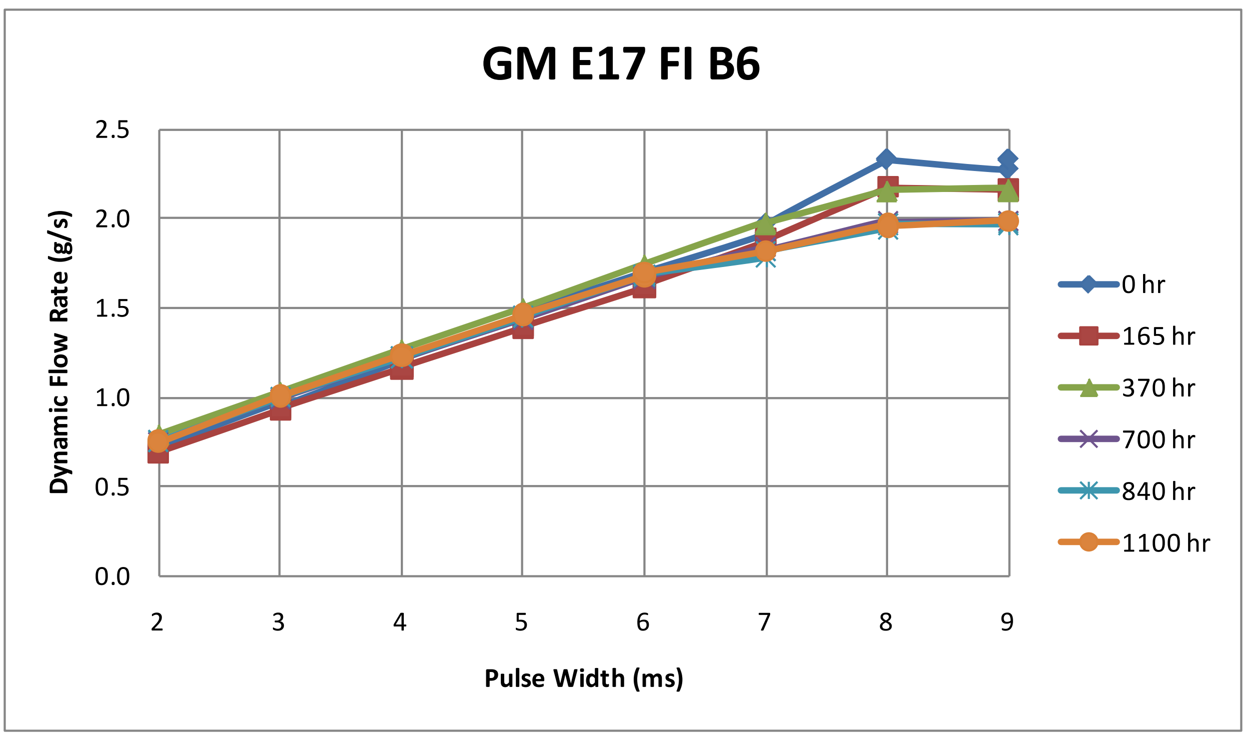

Figure A48: Dynamic flow rate of GM E17 fuel injector B6

Table A 6: Toyota E10 Fuel Injector Data

Toyota E10				
0	**hours**			
Injector	**Static Flow Rate**	**Slope**	**Flow Offset**	**LFR**
G2	2.950	2.454	4.846	2.199
G5	2.933	2.492	6.041	1.993
F3	2.900	2.372	6.036	2.010
G4	2.950	2.413	5.251	2.129
E1	2.917	2.371	5.319	2.107
F6	2.900	2.423	6.586	1.907
Average	**2.925**	**2.421**	**5.680**	**2.058**
Std. Dev.	**0.023**	**0.047**	**0.646**	**0.106**
175.5	**hours**			
Injector	**Static Flow Rate**	**Slope**	**Flow Offset**	**LFR**
G2	3.117	2.730	5.346	2.101
G5	3.100	2.700	6.616	1.885
F3	3.067	2.681	6.207	1.940
G4	3.117	2.769	5.205	2.115
E1	3.100	2.720	5.410	2.077
F6	3.050	2.861	6.769	1.908
Average	**3.092**	**2.744**	**5.925**	**2.004**
Std. Dev.	**0.027**	**0.065**	**0.691**	**0.104**
396	**hours**			
Injector	**Static Flow Rate**	**Slope**	**Flow Offset**	**LFR**
G2	2.950	2.790	4.437	2.205
G5	2.933	2.737	5.647	2.000
F3	2.917	2.694	5.249	2.056
G4	2.967	2.901	3.885	2.291
E1	2.917	2.659	4.893	2.132
F6	2.667	2.798	5.668	2.078
Average	**2.892**	**2.763**	**4.963**	**2.127**
Std. Dev.	**0.112**	**0.087**	**0.706**	**0.106**
811.5	**hours**			
Injector	**Static Flow Rate**	**Slope**	**Flow Offset**	**LFR**
G2	2.983	2.794	4.497	2.130
G5	2.967	2.724	5.748	1.958
F3	2.950	2.677	5.344	2.021
G4	2.983	2.738	4.805	2.144
E1	2.950	2.669	4.810	2.146
F6	2.933	2.737	6.221	2.009
Average	**2.961**	**2.723**	**5.238**	**2.068**
Std. Dev.	**0.020**	**0.046**	**0.657**	**0.082**

Toyota E10				
0	**hours**			
Injector	**Static Flow Rate**	**Slope**	**Flow Offset**	**LFR**
1664	**hours**			
Injector	**Static Flow Rate**	**Slope**	**Flow Offset**	**LFR**
G2	2.733	1.894	7.762	1.638
G5	2.700	1.790	9.062	1.540
F3	2.667	1.688	9.401	1.519
G4	2.733	1.826	8.319	1.597
E1	2.683	1.709	8.522	1.605
F6	2.667	1.627	10.370	1.469
Average	**2.697**	**1.756**	**8.906**	**1.561**
Std. Dev.	**0.031**	**0.099**	**0.918**	**0.063**

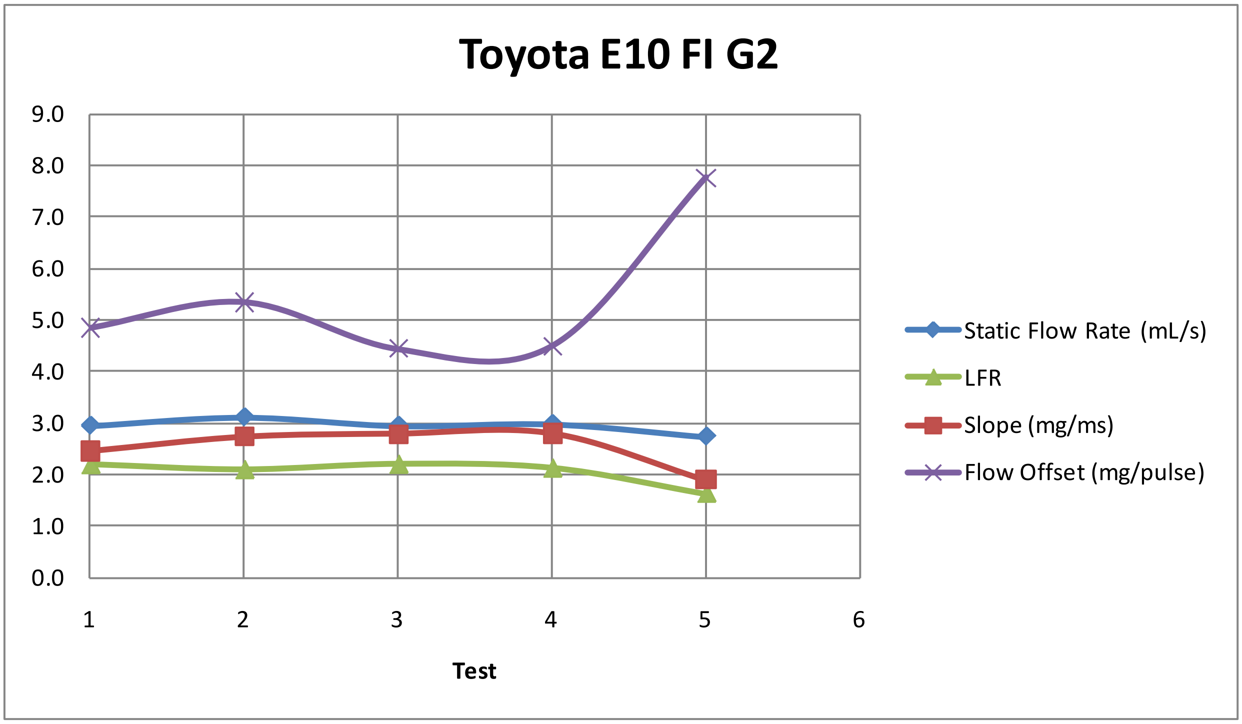

Figure A49: Significant parameters of Toyota E10 fuel injector G2

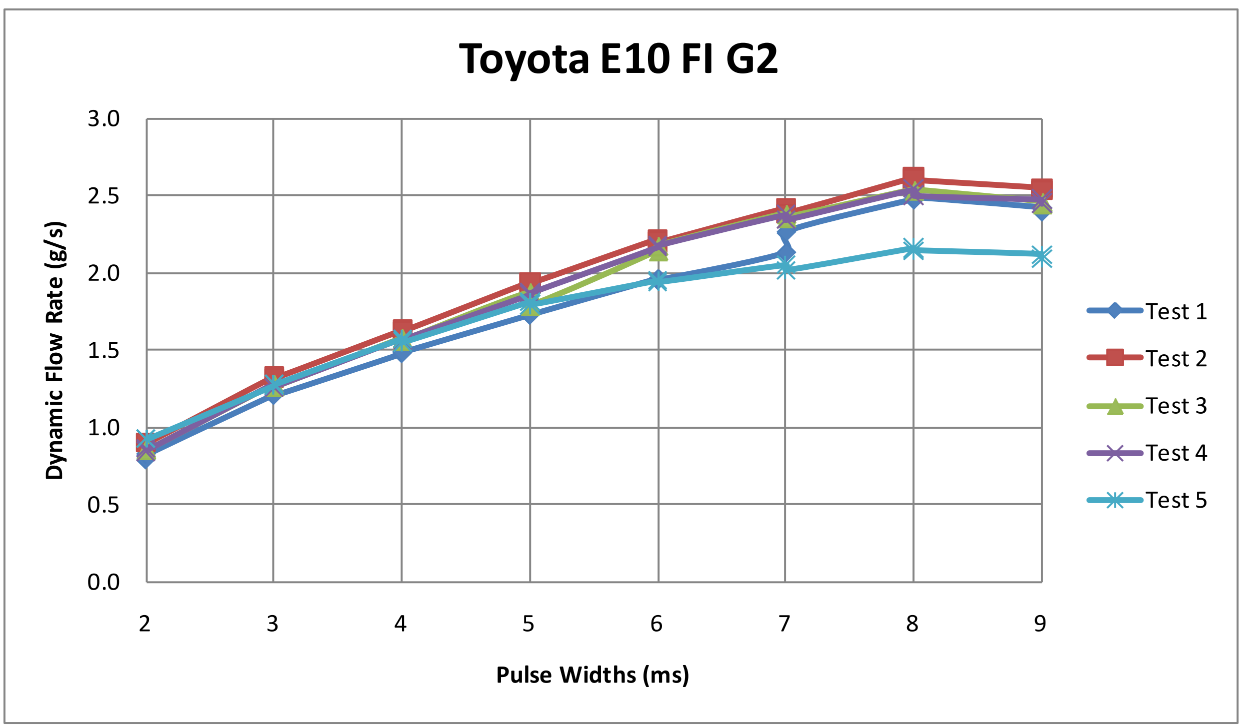

Figure A50: Dynamic flow rate of Toyota E10 fuel injector G2

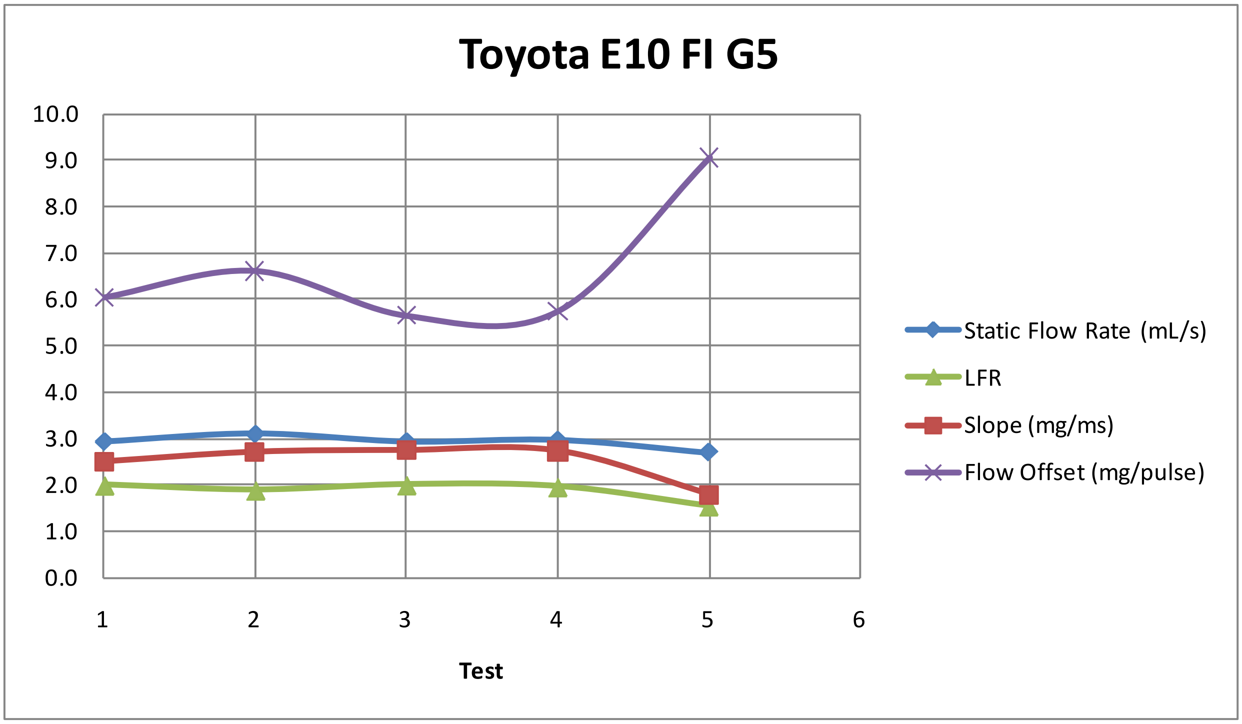

Figure A51: Significant parameters of Toyota E10 fuel injector G5

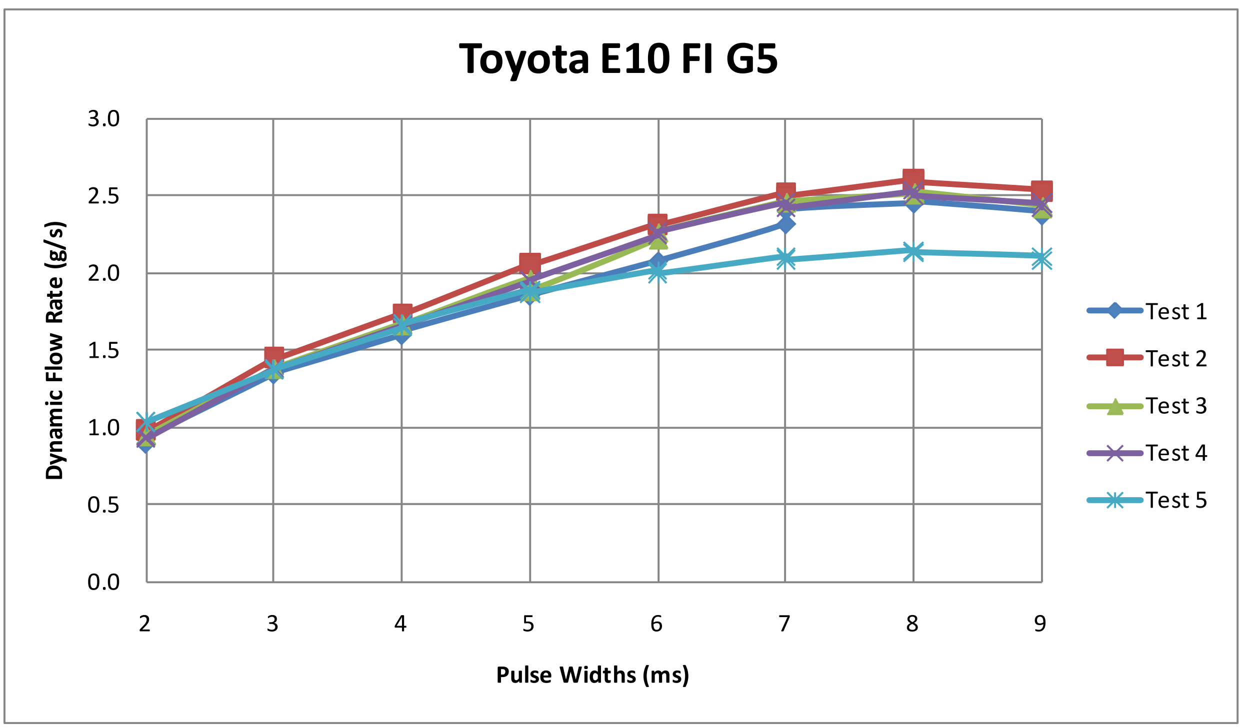

Figure A52: Dynamic flow rate of Toyota E10 fuel injector G5

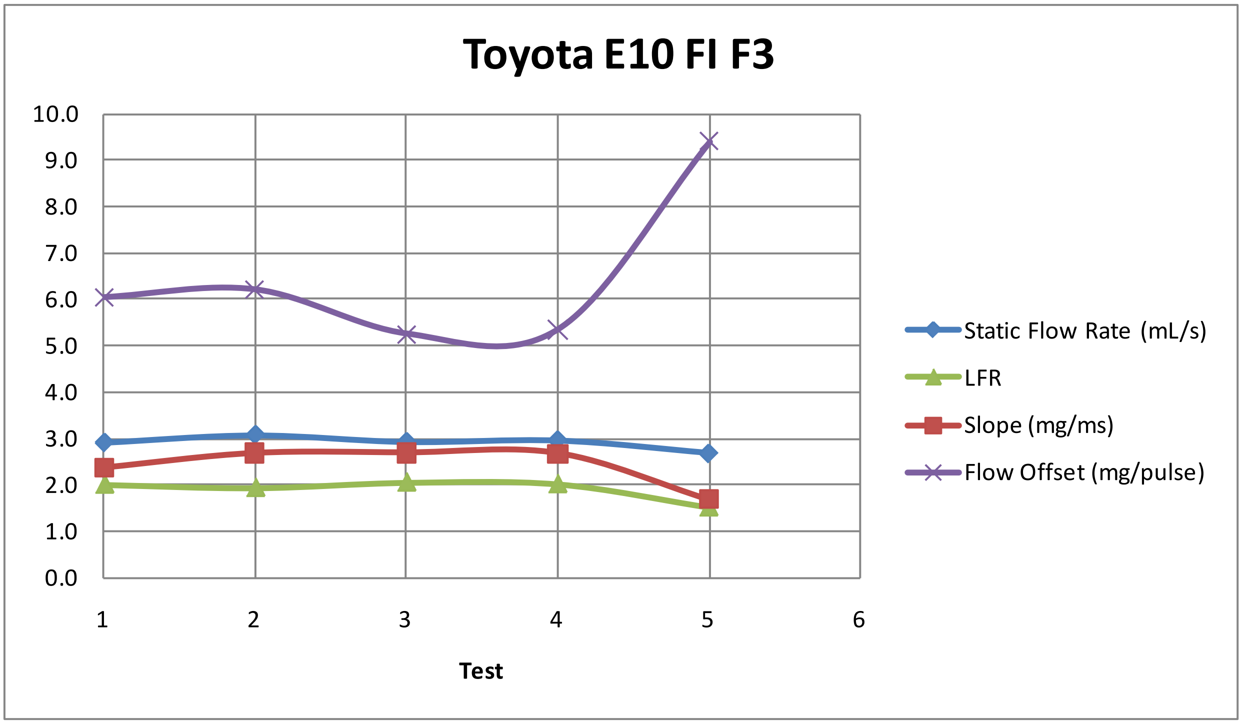

Figure A53: Significant parameters of Toyota E10 fuel injector F3

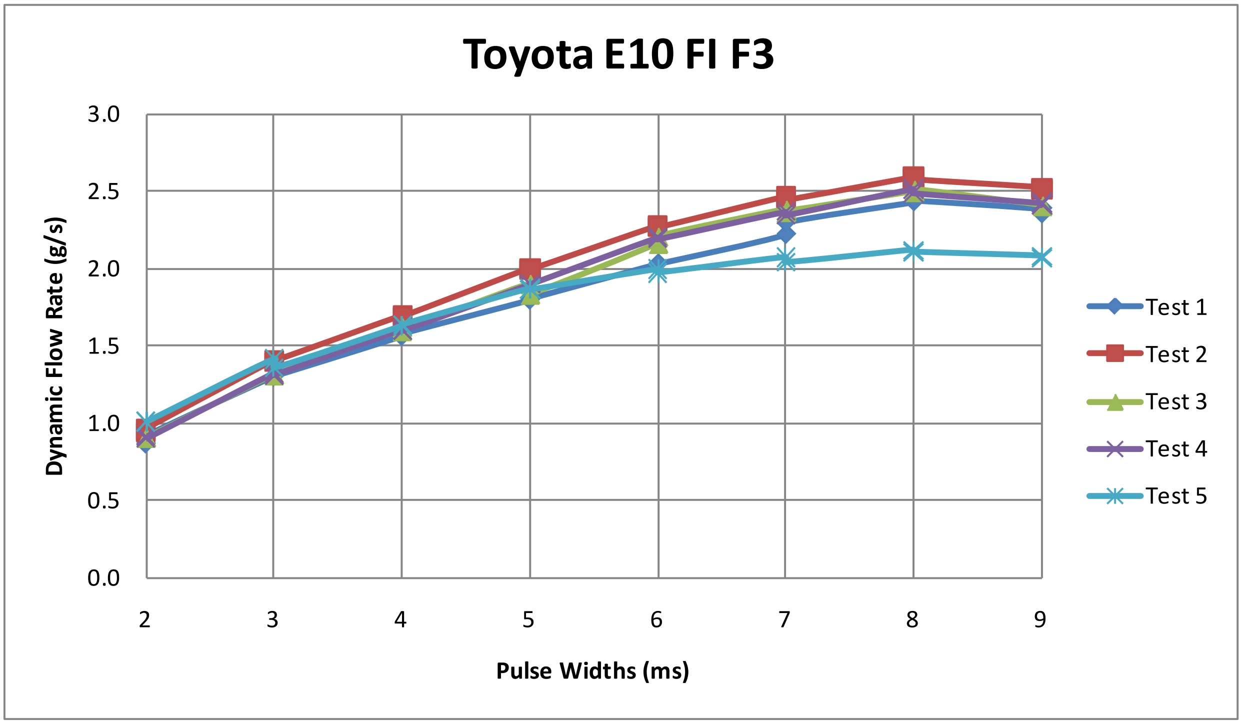

Figure A54: Dynamic flow rate of Toyota E10 fuel injector F3

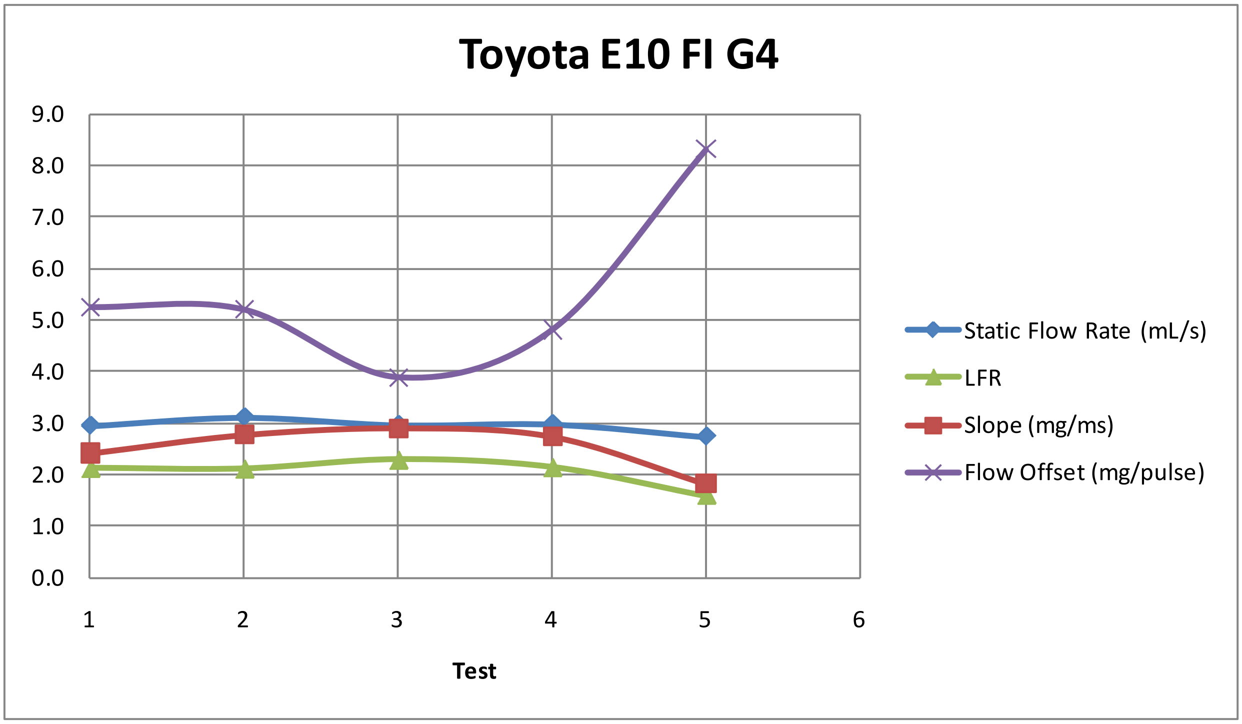

Figure A55: Significant Parameters of Toyota E10 fuel injector G4

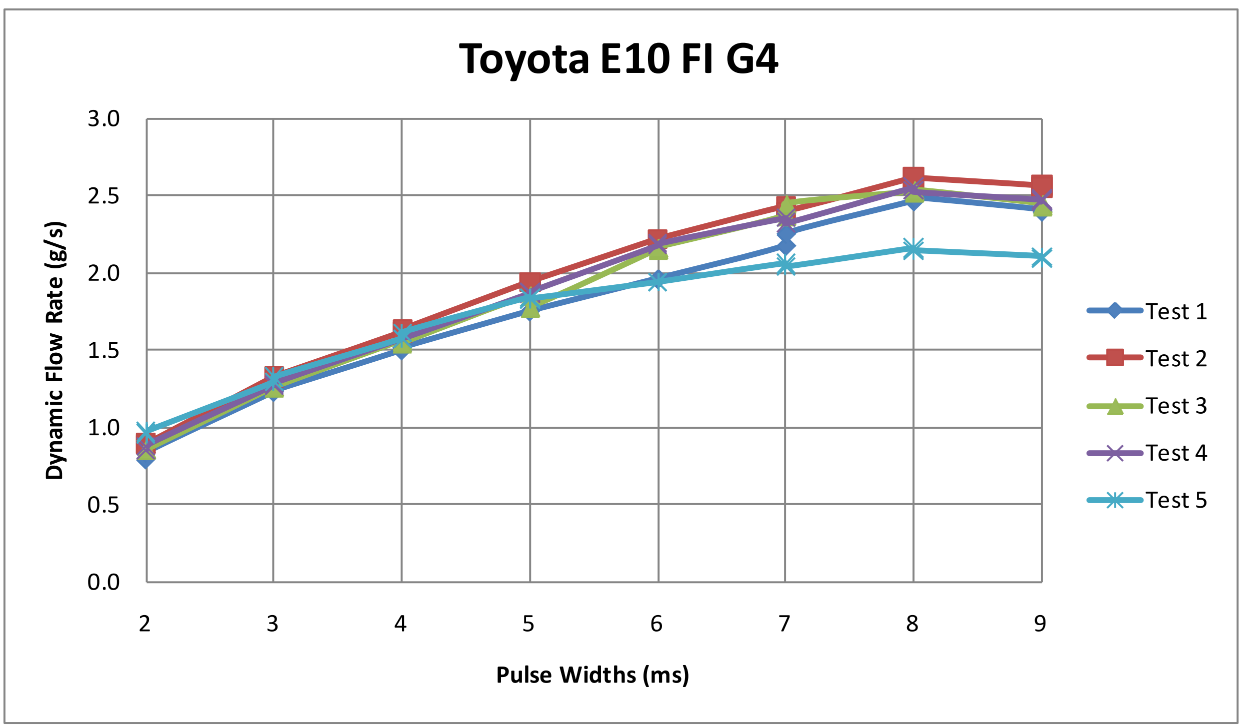

Figure A56: Dynamic flow rate of Toyota E10 fuel injector G4

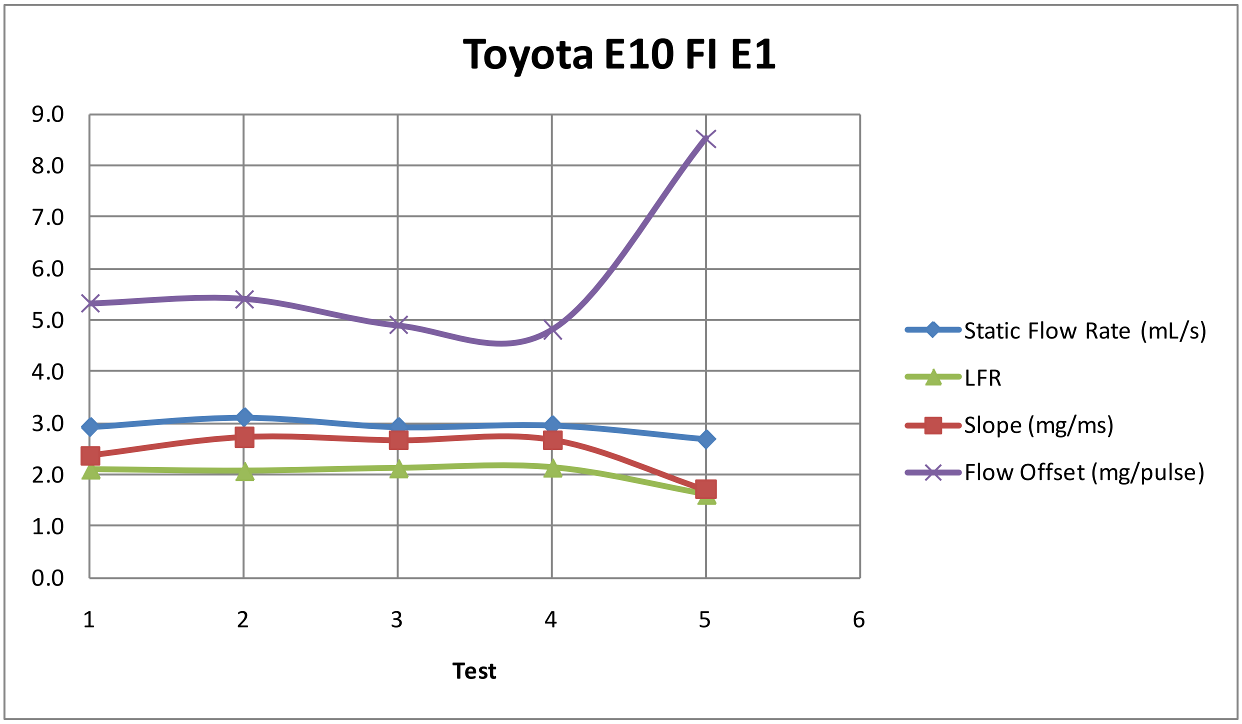

Figure A57: Significant parameters of Toyota E10 fuel injector E1

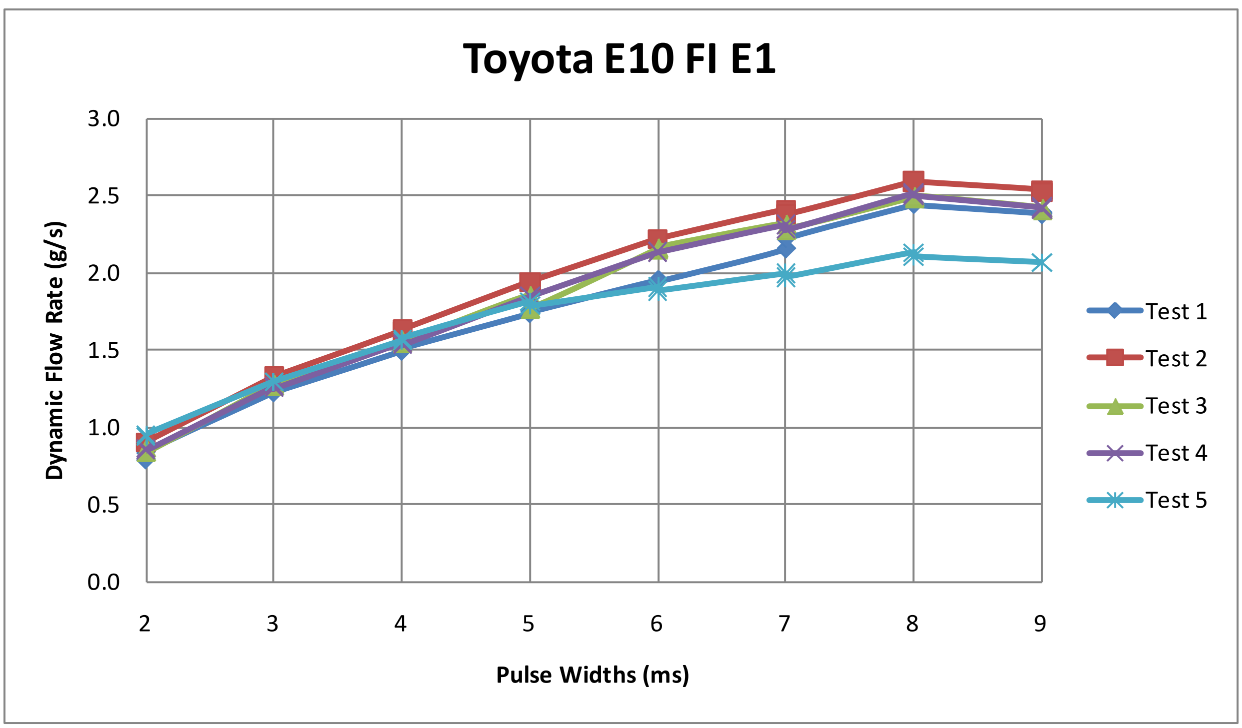

Figure A58: Dynamic flow rate of Toyota E10 fuel injector E1

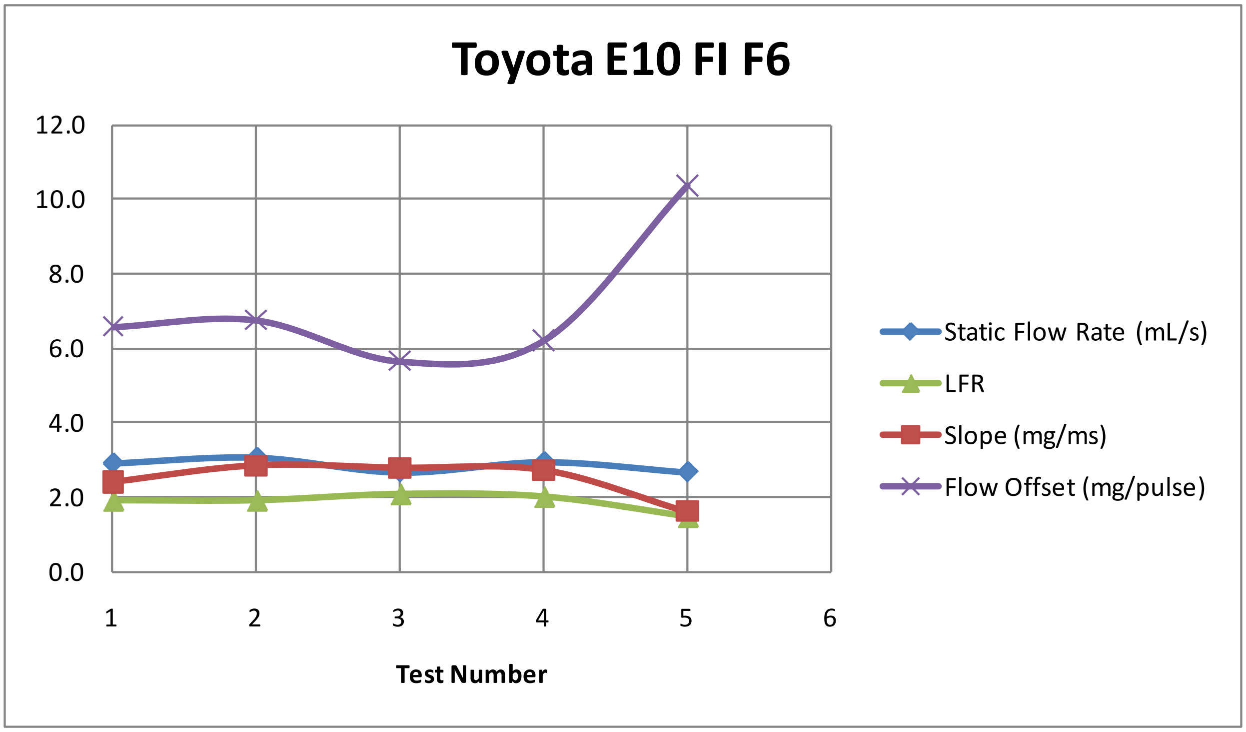

Figure A59: Significant parameters of Toyota E10 fuel injector F6

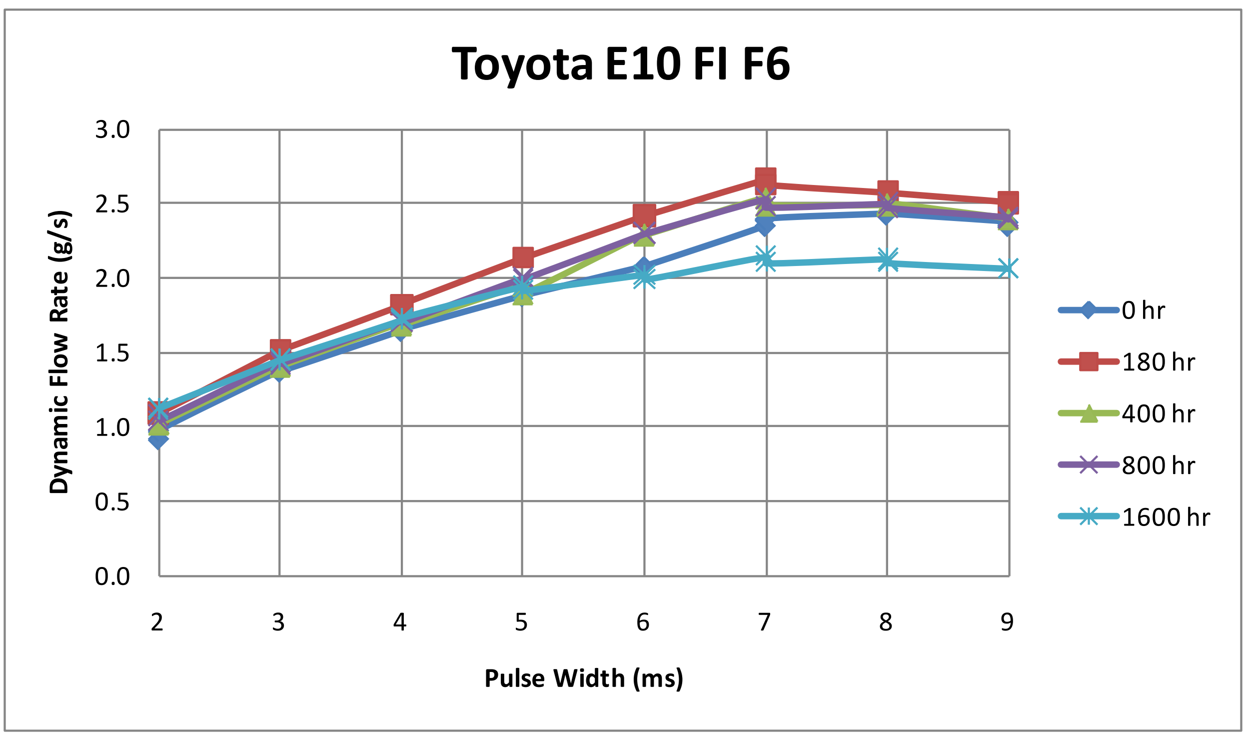

Figure A60: Dynamic Flow Rate of Toyota E10 fuel injector F6

Table A7: Toyota E17 Fuel Injector Data

Toyota E17				
0	**hours**			
Injector	**Static Flow Rate**	**Slope**	**Flow Offset**	**LFR**
G6	3.300	2.935	5.684	2.111
E2	2.917	2.741	4.232	2.259
E3	3.167	2.769	5.497	2.103
E4	3.017	2.664	4.891	2.140
E5	3.133	2.922	4.958	2.129
E6	3.183	3.016	3.511	2.333
Average	**3.119**	**2.841**	**4.795**	**2.179**
Std. Dev.	**0.135**	**0.136**	**0.811**	**0.094**
158.3	**hours**			
Injector	**Static Flow Rate**	**Slope**	**Flow Offset**	**LFR**
G6	3.117	2.964	3.745	2.282
E2	2.967	2.773	4.068	2.231
E3	3.000	2.831	4.361	2.189
E4	2.967	2.754	4.219	2.228
E5	3.067	2.810	4.818	2.113
E6	3.050	2.838	3.719	2.311
Average	**3.028**	**2.828**	**4.155**	**2.226**
Std. Dev.	**0.060**	**0.074**	**0.413**	**0.070**
369	**hours**			
Injector	**Static Flow Rate**	**Slope**	**Flow Offset**	**LFR**
G6	3.067	2.927	3.902	2.255
E2	2.950	2.735	4.607	2.117
E3	2.983	2.796	4.679	2.114
E4	2.933	2.744	4.543	2.176
E5	3.017	2.791	5.228	2.062
E6	3.017	2.839	3.948	2.269
Average	**2.994**	**2.805**	**4.484**	**2.166**
Std. Dev.	**0.049**	**0.071**	**0.497**	**0.083**
702.8	**hours**			
Injector	**Static Flow Rate**	**Slope**	**Flow Offset**	**LFR**
G6	3.000	2.640	5.168	1.921
E2	2.917	2.384	6.296	1.834
E3	2.917	2.400	6.505	1.785
E4	2.900	2.356	6.307	1.810
E5	2.950	2.292	7.398	1.685
E6	2.867	2.364	6.233	1.796
Average	**2.925**	**2.406**	**6.318**	**1.805**
Std. Dev.	**0.046**	**0.120**	**0.712**	**0.077**

844.5	**hours**			
Injector	**Static Flow Rate**	**Slope**	**Flow Offset**	**LFR**
G6	2.750	2.186	6.834	1.737
E2	2.767	2.111	7.959	1.642
E3	2.800	2.189	6.565	1.776
E4	2.833	2.395	5.812	1.844
E5	2.767	2.279	6.605	1.754
E6	2.750	2.200	7.032	1.711
Average	**2.778**	**2.227**	**6.801**	**1.744**
Std. Dev.	**0.033**	**0.098**	**0.703**	**0.067**
1,104	**hours**			
Injector	**Static Flow Rate**	**Slope**	**Flow Offset**	**LFR**
G6	2.833	2.376	6.020	1.729
E2	2.767	2.242	7.070	1.546
E3	2.767	2.228	6.911	1.897
E4	2.750	2.185	7.155	1.943
E5	2.767	2.197	7.652	1.857
E6	2.783	2.220	6.683	1.591
Average	**2.778**	**2.241**	**6.915**	**1.760**
Std. Dev.	**0.029**	**0.069**	**0.544**	**0.165**

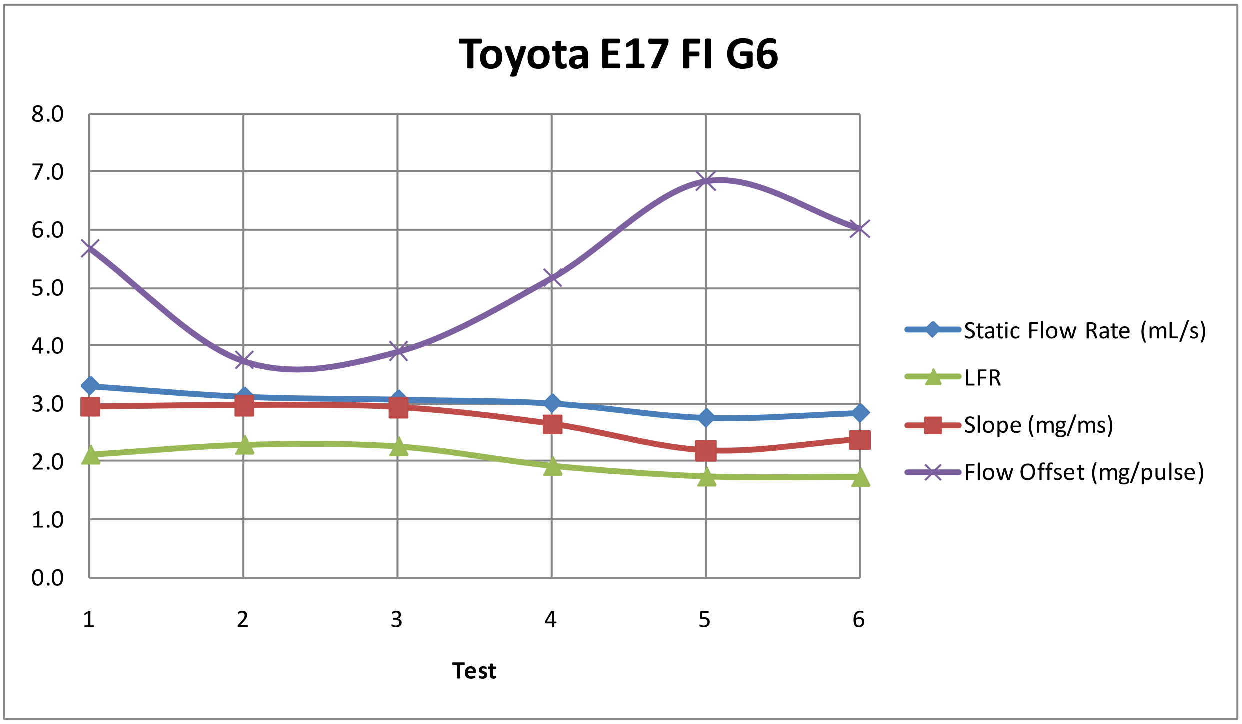

Figure A61: Significant parameters of Toyota E17 fuel injector G6

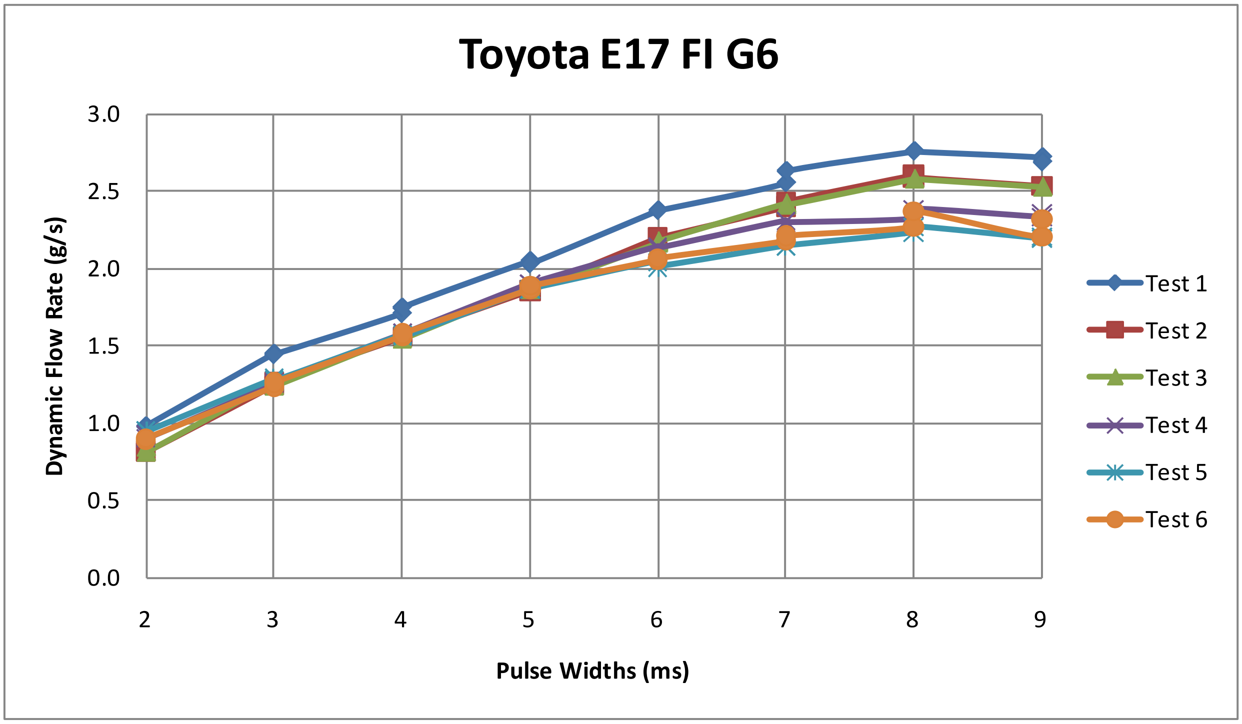

Figure A62: Dynamic flow rate of Toyota E17 fuel injector G6

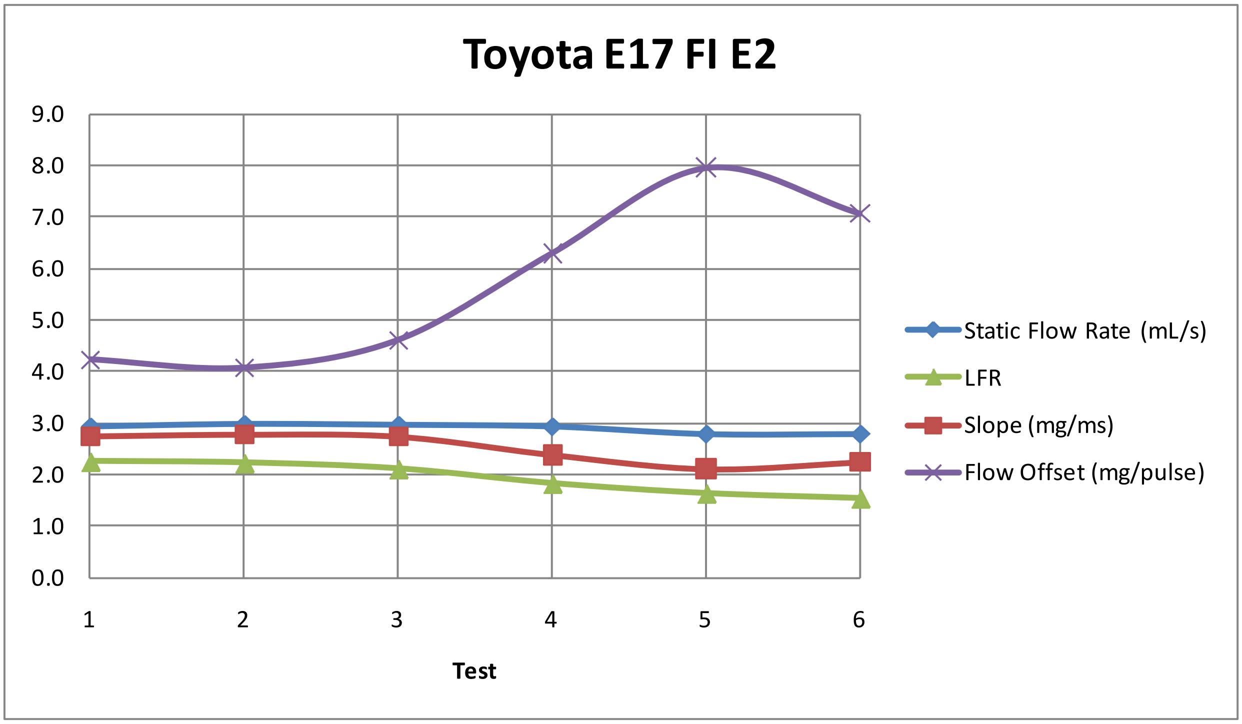

Figure A63: Significant parameters of Toyota E17 fuel injector E2

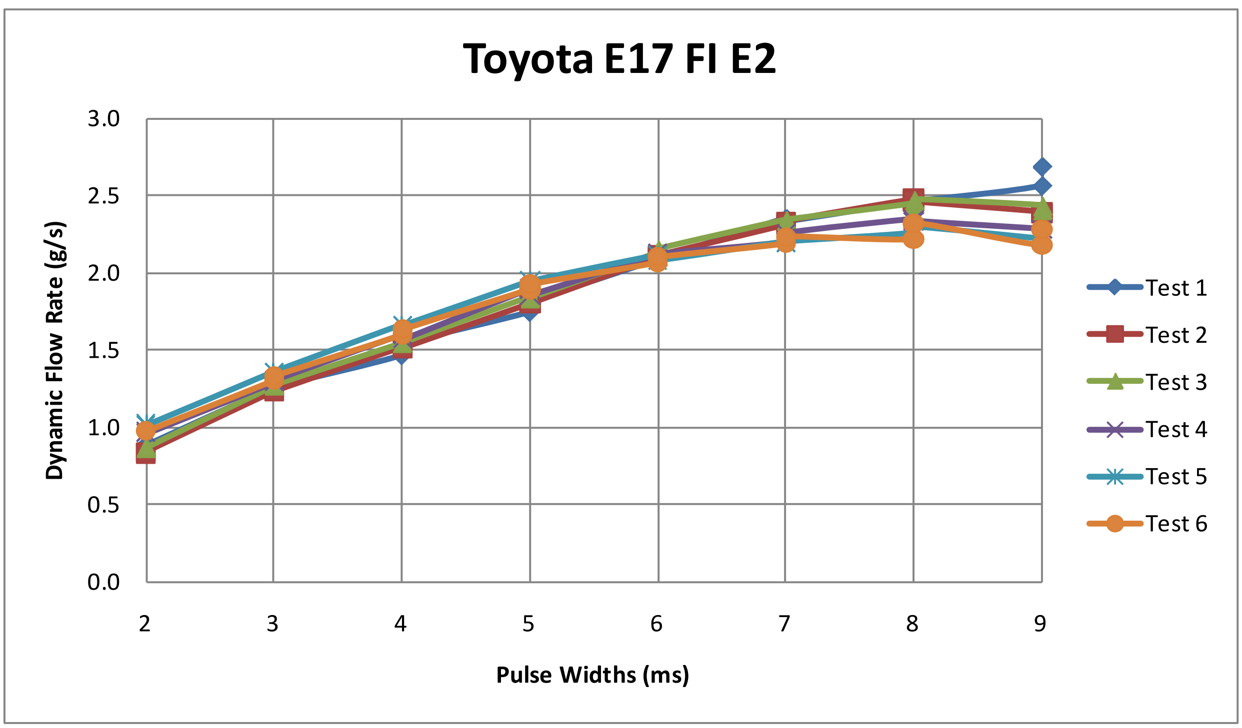

Figure A64: Dynamic flow rate of Toyota E17 fuel injector E2

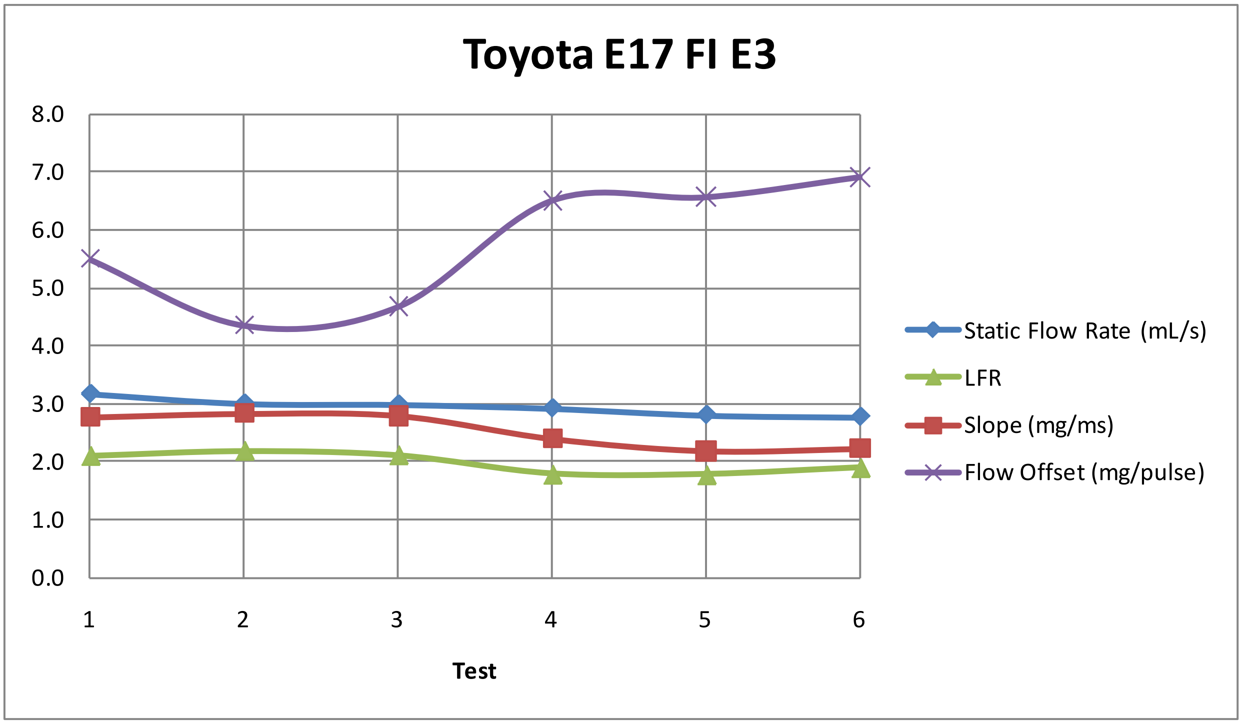

Figure A65: Significant parameters of Toyota E17 fuel injector E3

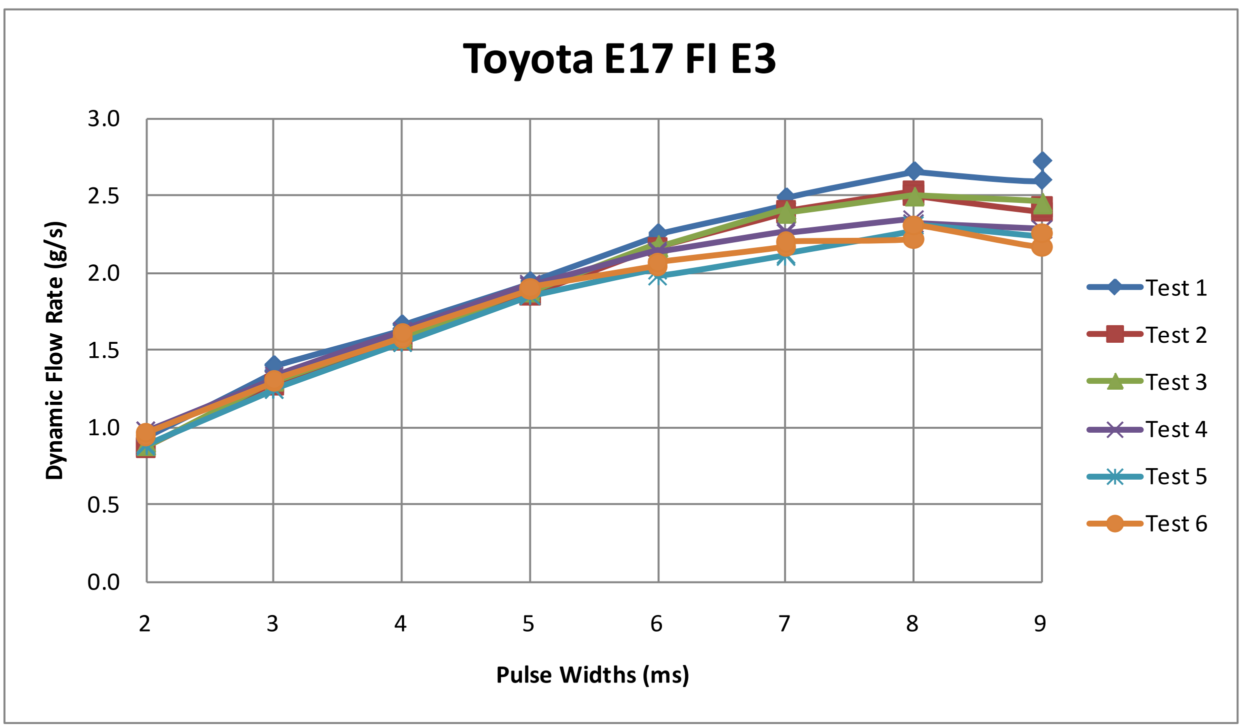

Figure A66: Dynamic flow rate of Toyota E17 fuel injector E3

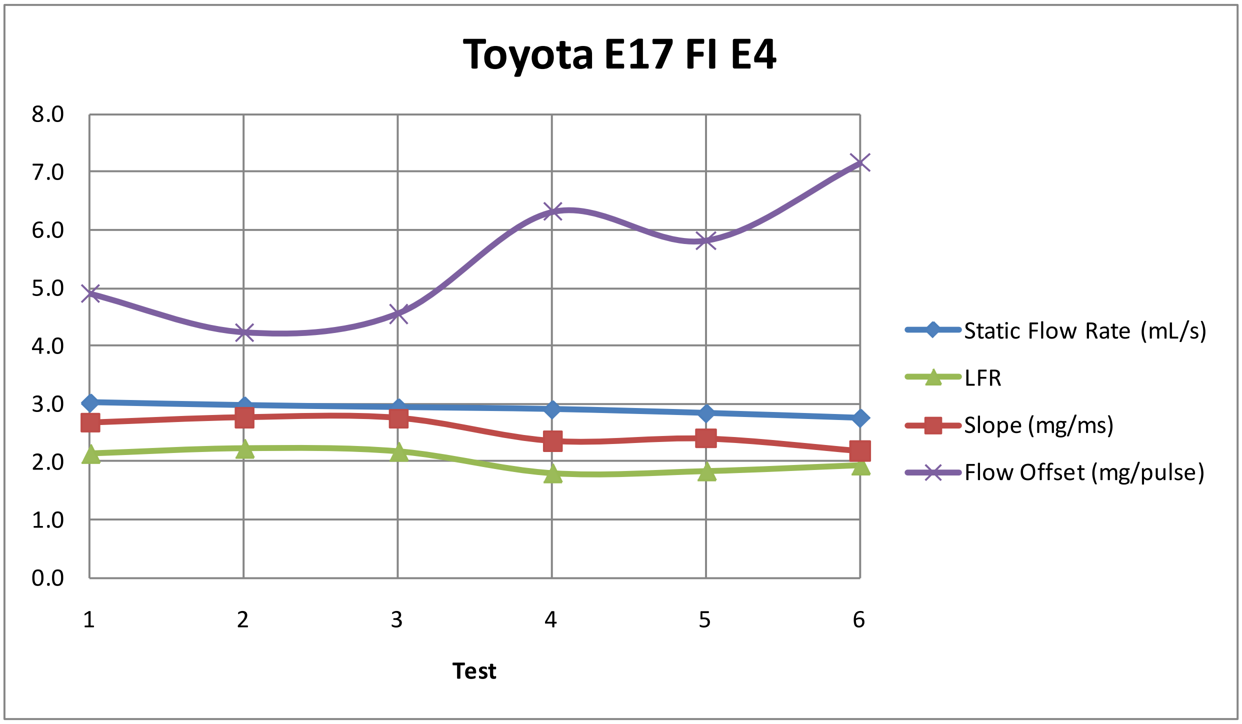

Figure A67: Significant parameters of Toyota E17 fuel injector E4

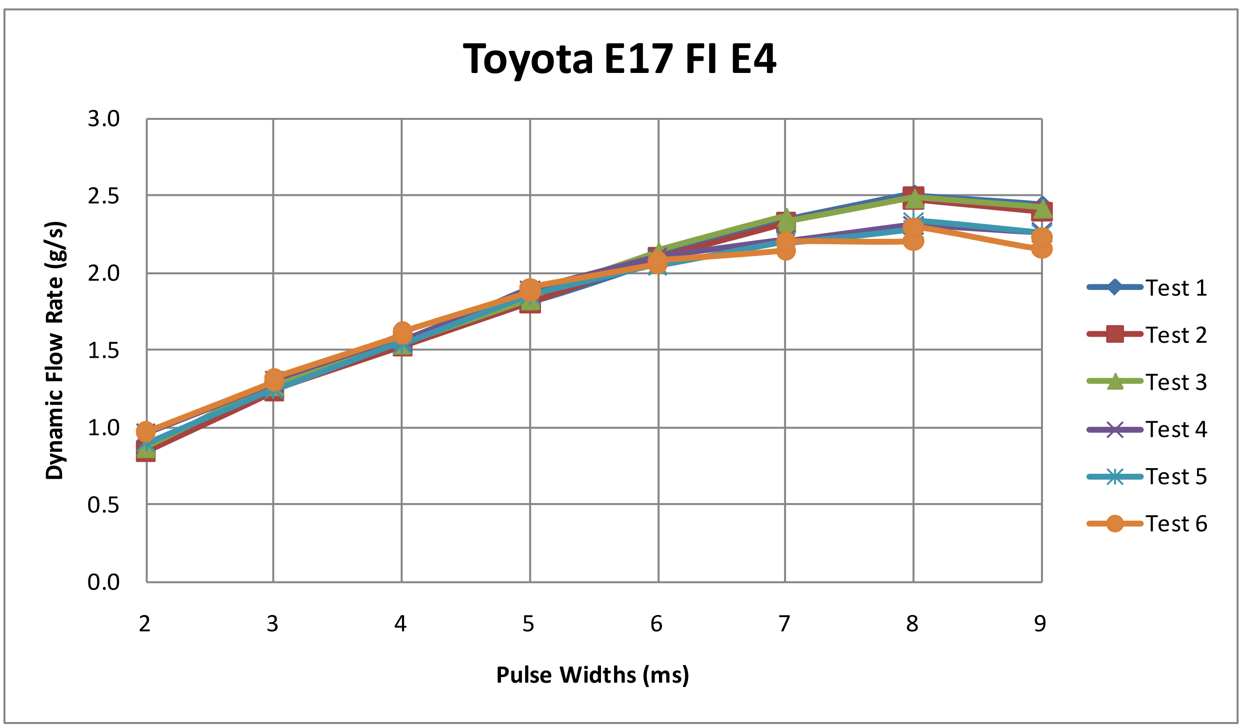

Figure A68: Dynamic flow rate of Toyota E17 fuel injector E4

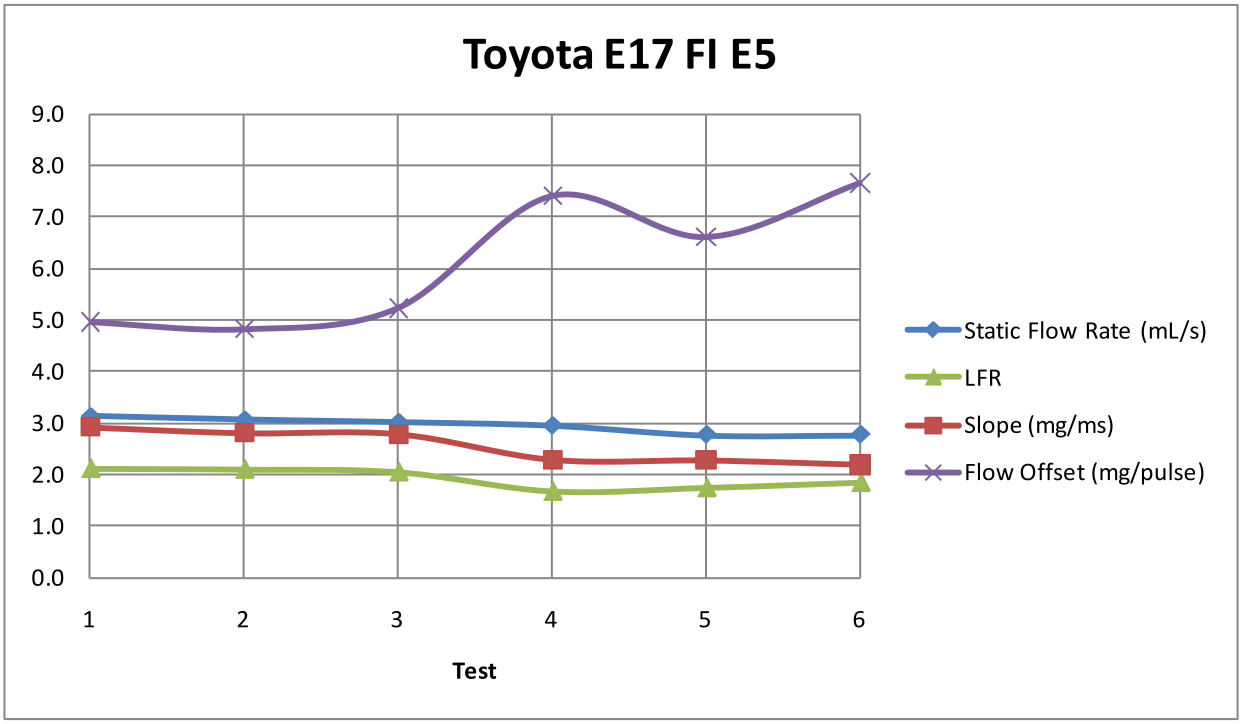

Figure A69: Significant parameters of Toyota E17 fuel injector E5

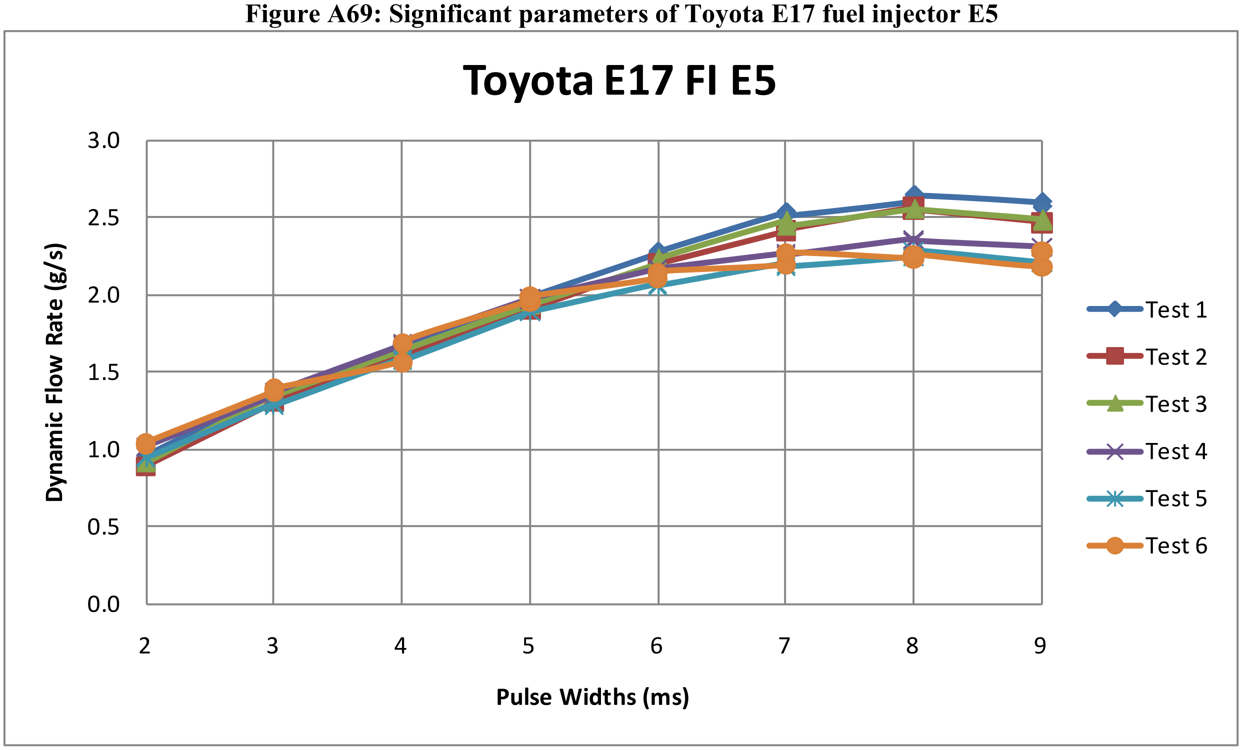

Figure A70: Dynamic flow rate of Toyota E17 fuel injector E5

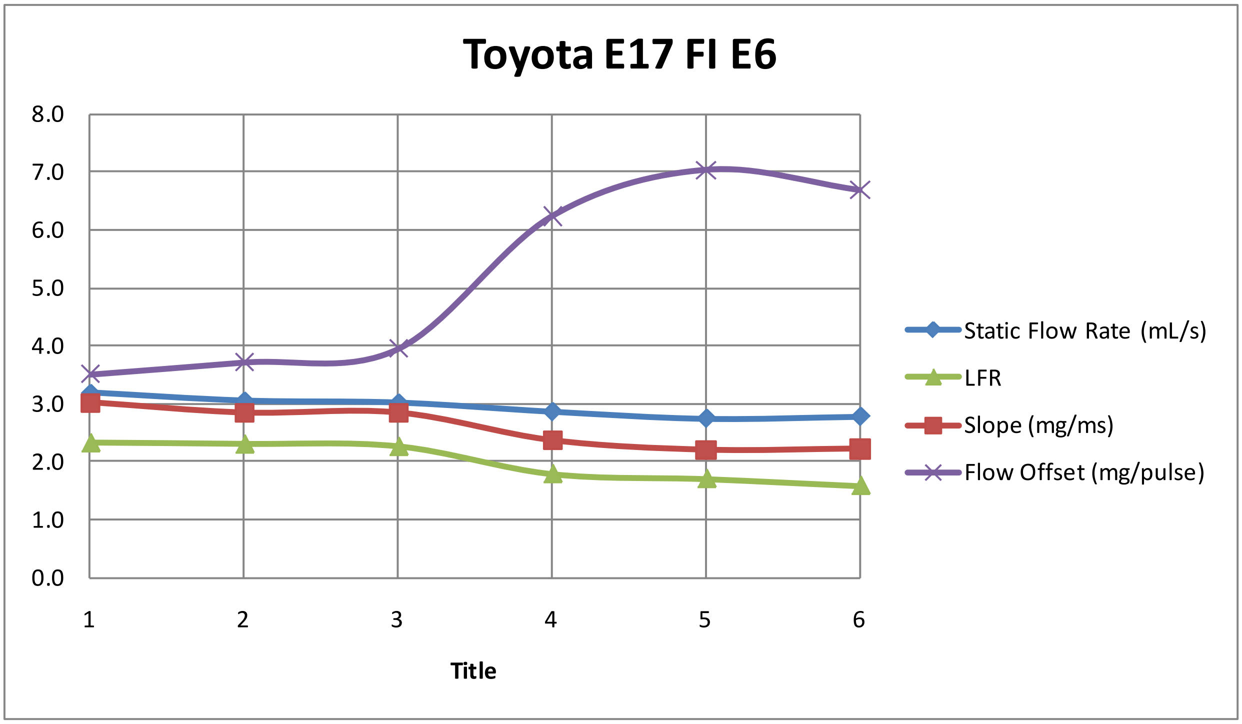

Figure A71: Significant parameters of Toyota E17 fuel injector E6

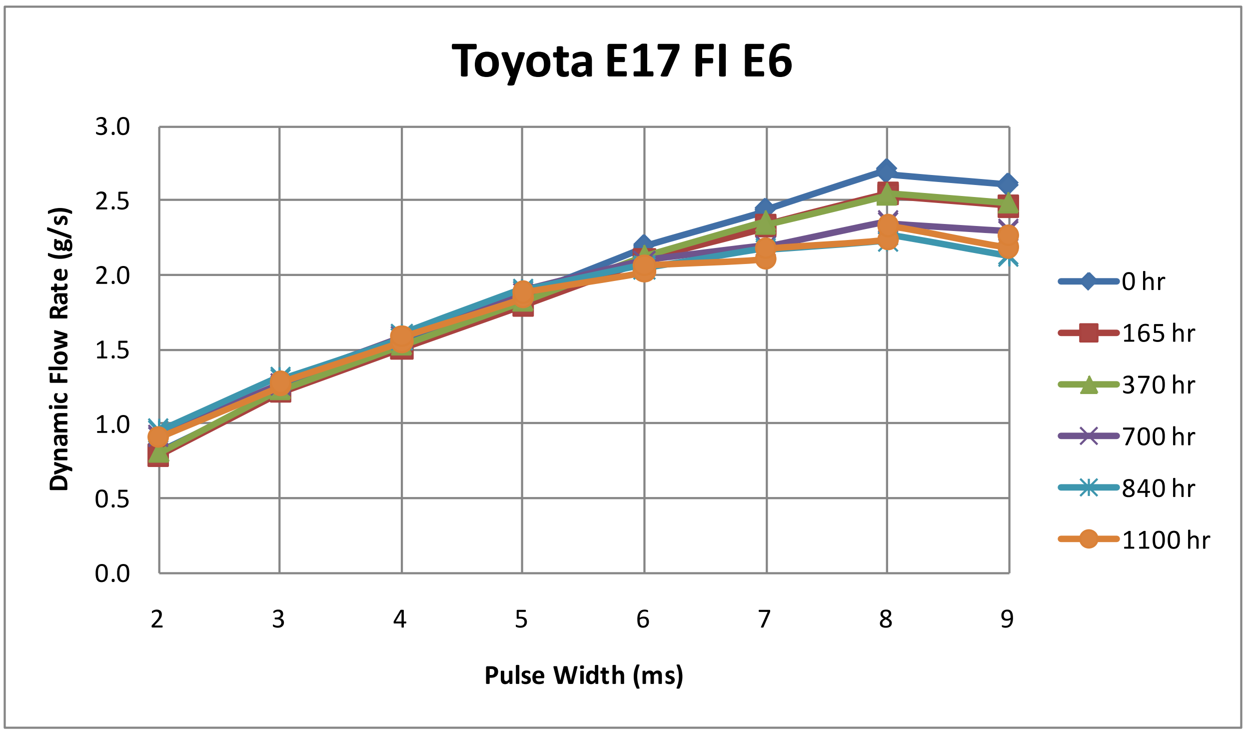

Figure A72: Dynamic flow rate of Toyota E17 fuel injector E6

Appendix B

Endurance Testing Data

This appendix presents data collected on the fuel systems while the test rigs were running the endurance tests. Data are provided for each system in the following order:

- Ford E10
- Ford E17
- GM E10
- GM E17
- Toyota E10
- Toyota E17

For each fuel system test rig, the data are presented in the following order:

- Pressure vs. Flow Rate
- Pressure, Flow, Rail Temp, Ambient Temp, Current Draw vs. Time – 0% Duty Cycle
- Pressure, Flow, Rail Temp, Ambient Temp, Current Draw vs. Time – 20% Duty Cycle
- Pressure, Flow, Rail Temp, Ambient Temp, Current Draw vs. Time – 50% Duty Cycle
- Pressure, Flow, Rail Temp, Ambient Temp, Current Draw vs. Time – 80% Duty Cycle

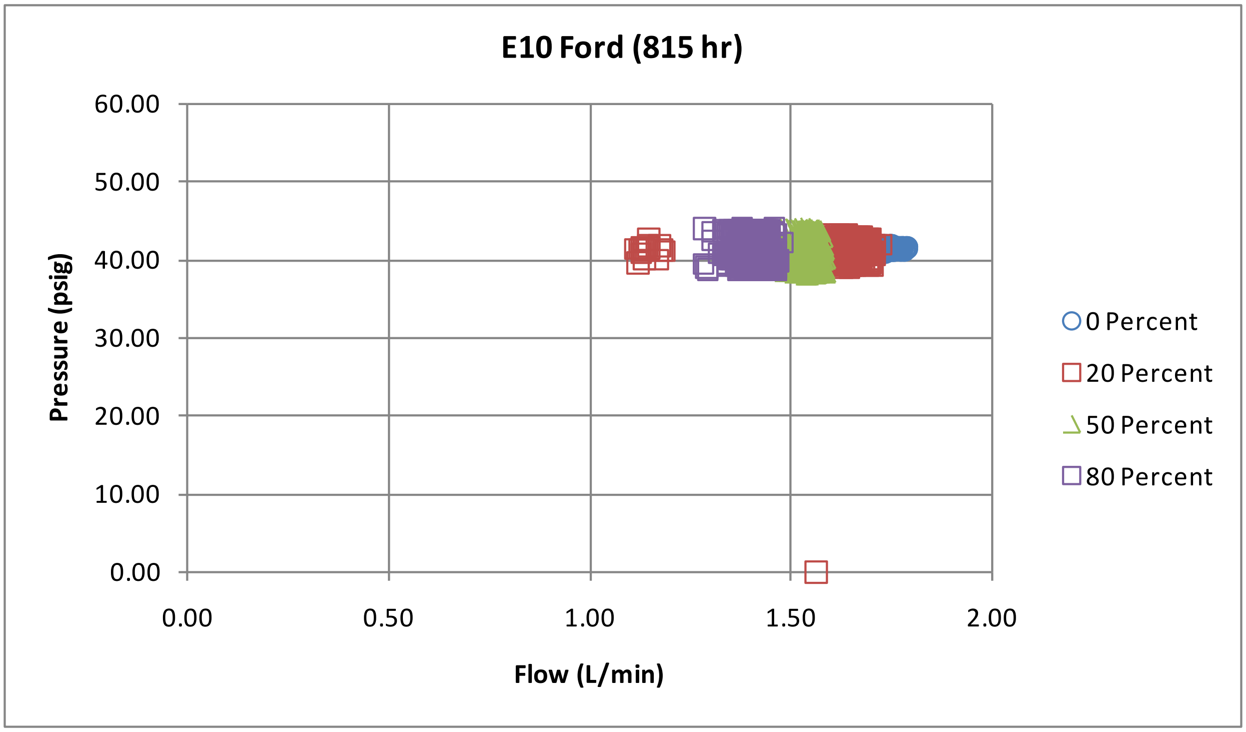

Figure B1: Ford E10 pump operating conditions (815 hr)

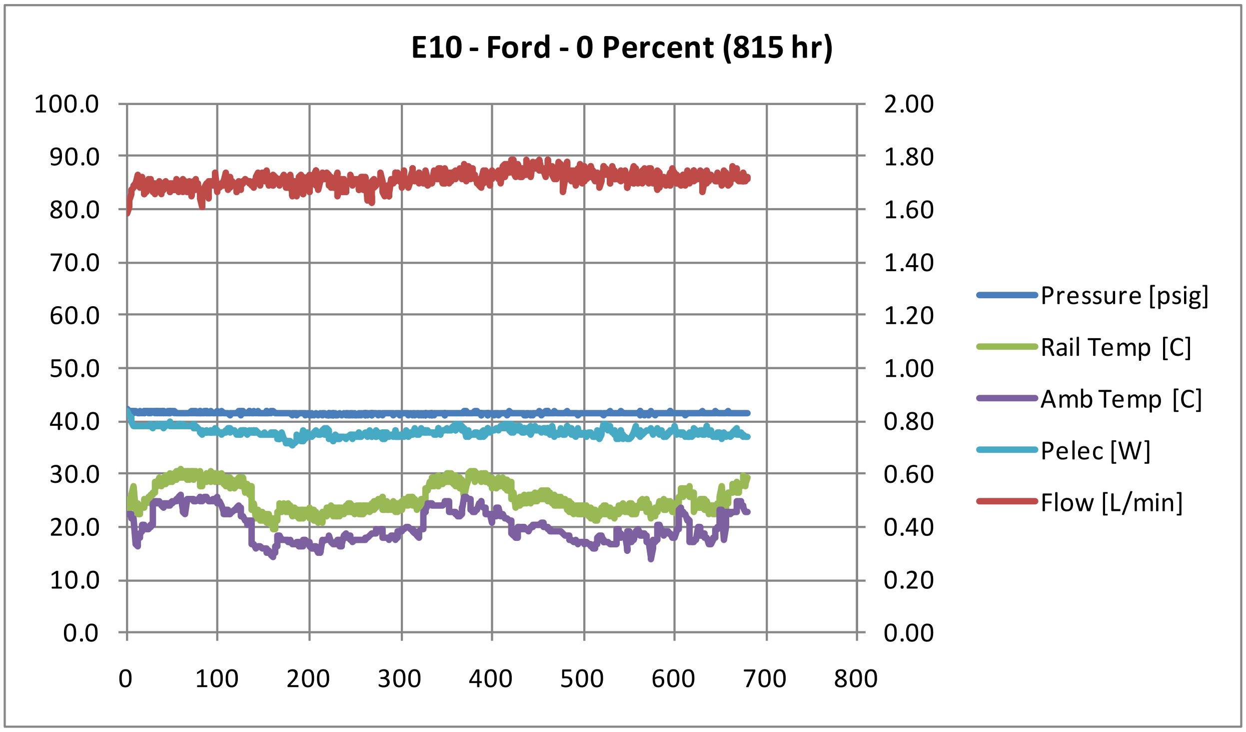

Figure B2: Ford E10 - 0 percent fuel injector pulse width on (815 hr)

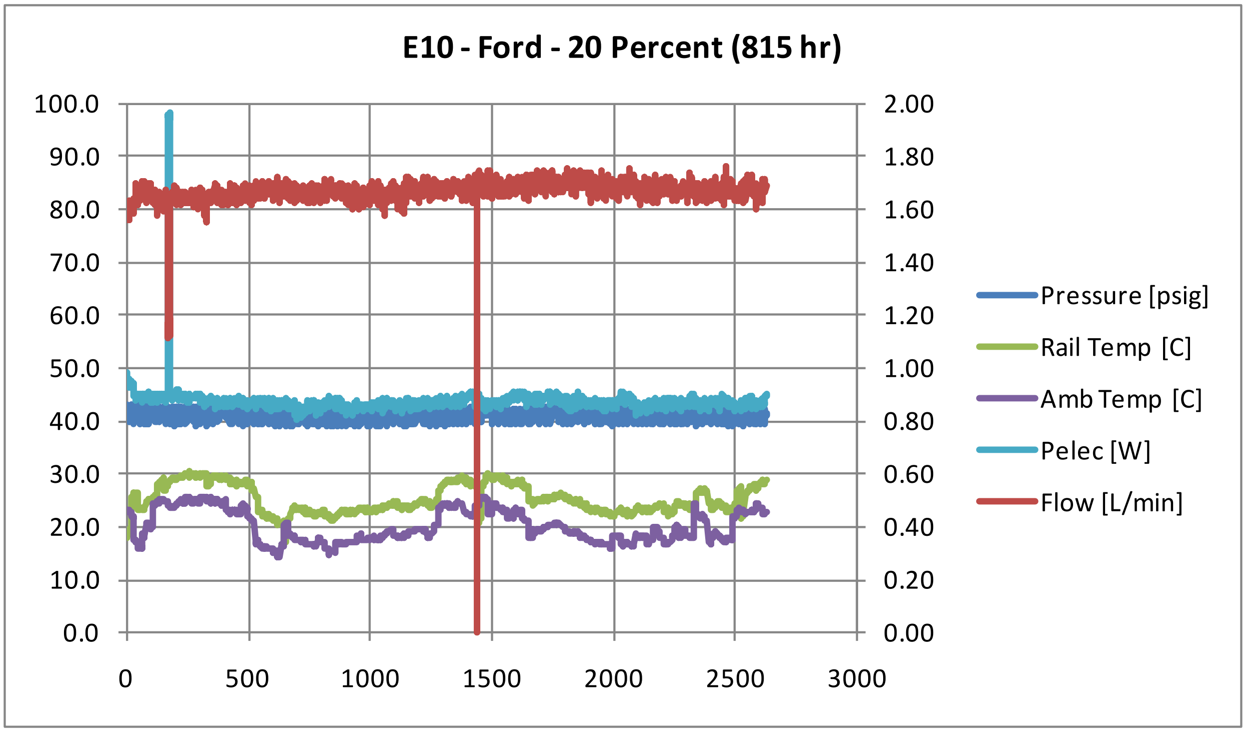

Figure B3: Ford E10 - 20 percent fuel injector pulse width on (815 hr)

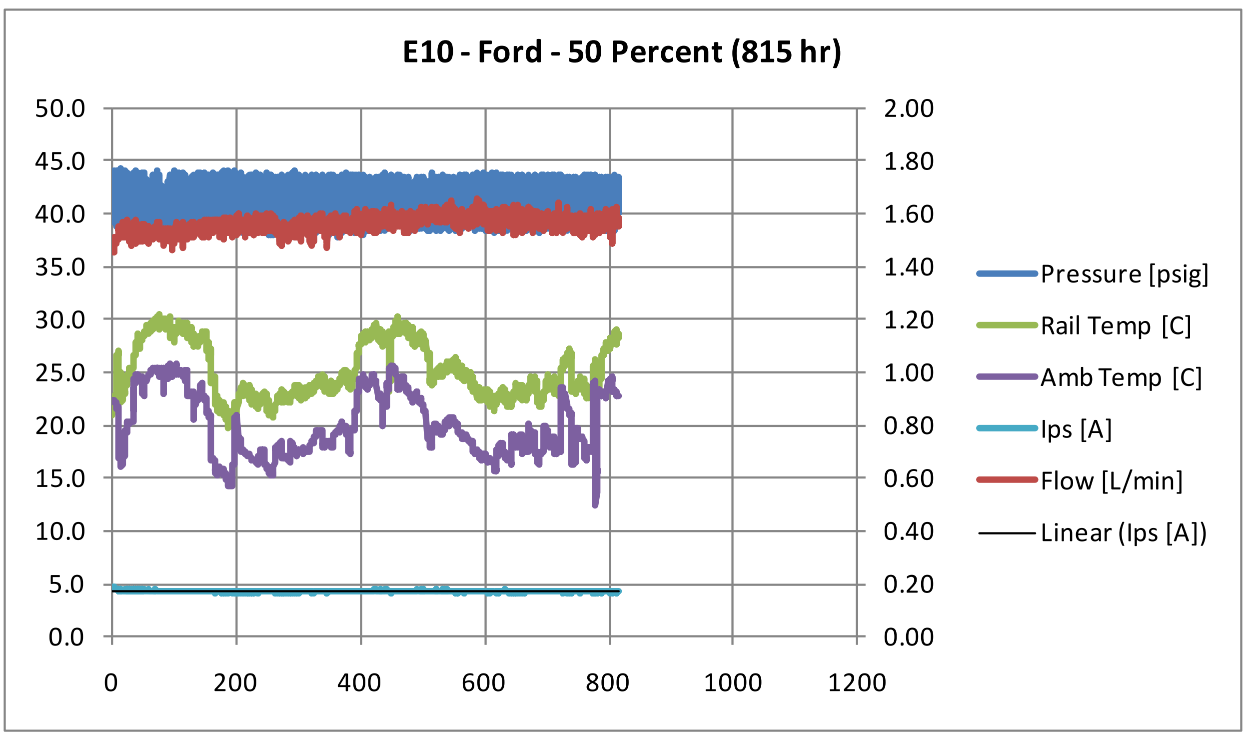

Figure B4: Ford E10 - 50 percent fuel injector pulse width on (815 hr)0.

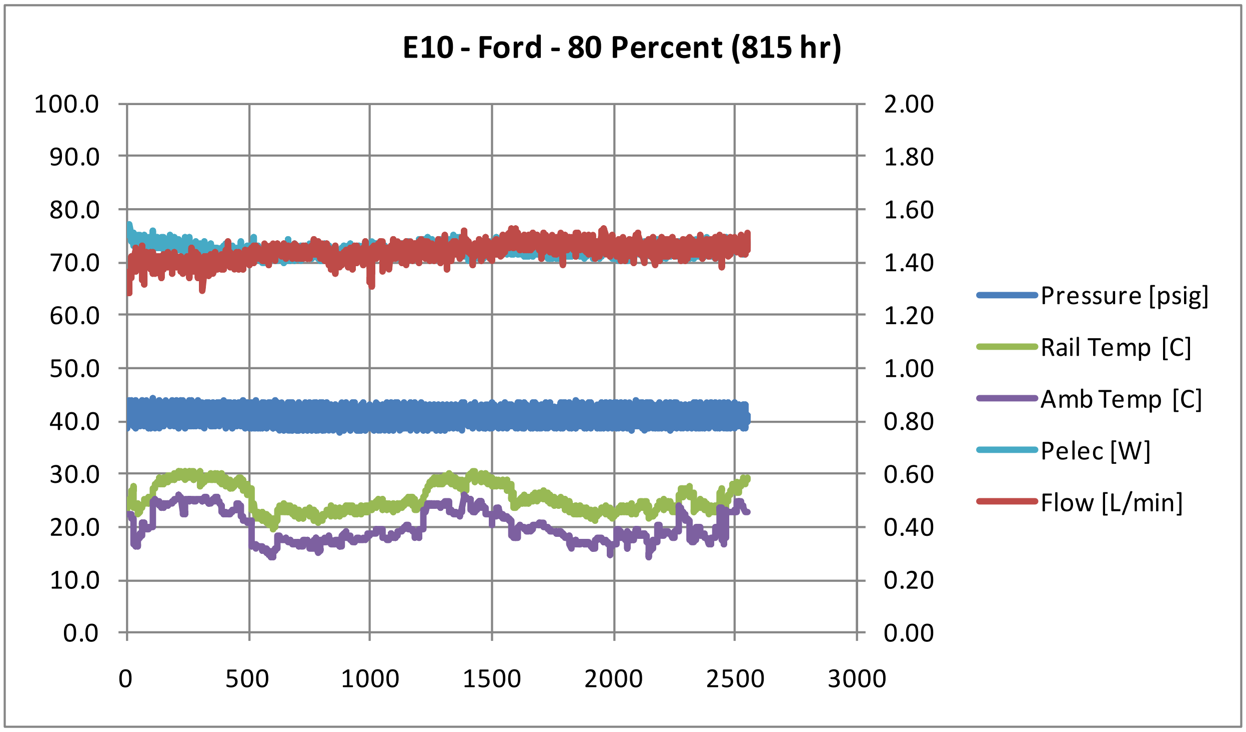

Figure B5: Ford E10 - 80 percent fuel injector pulse width on (815 hr)

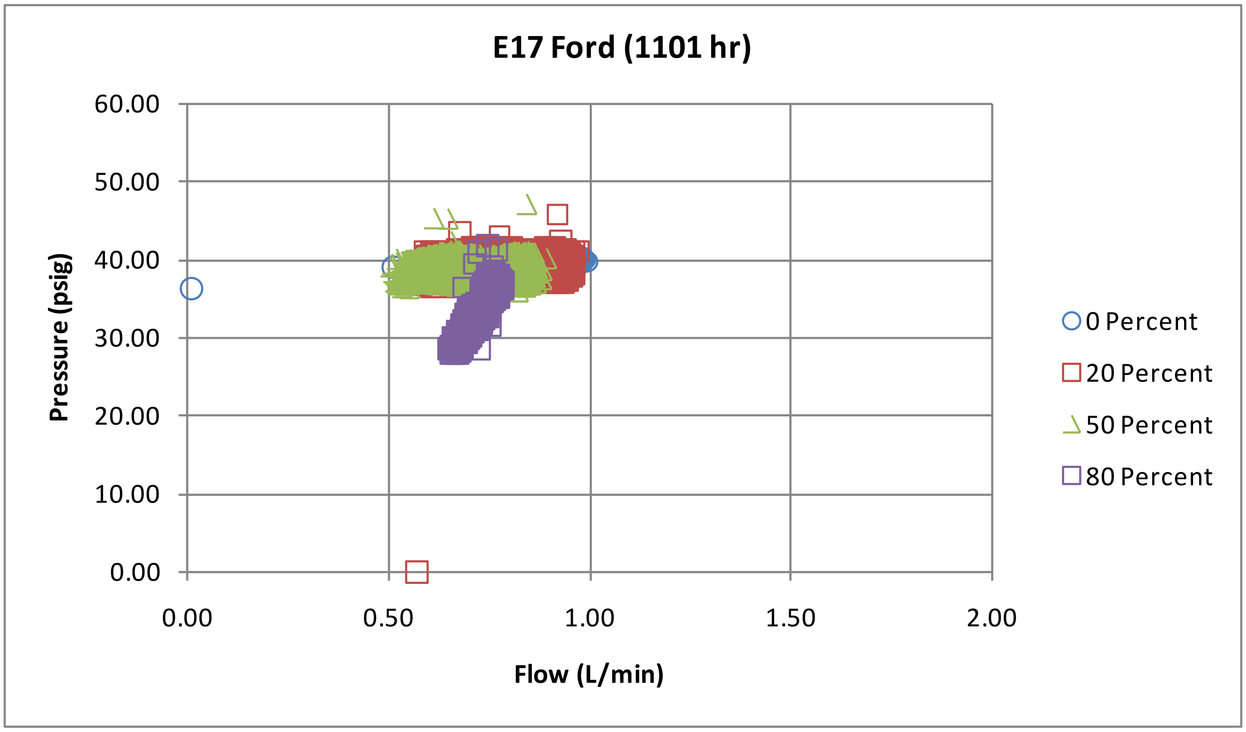

Figure B6: Ford E17 pump operating conditions (1,101 hr)

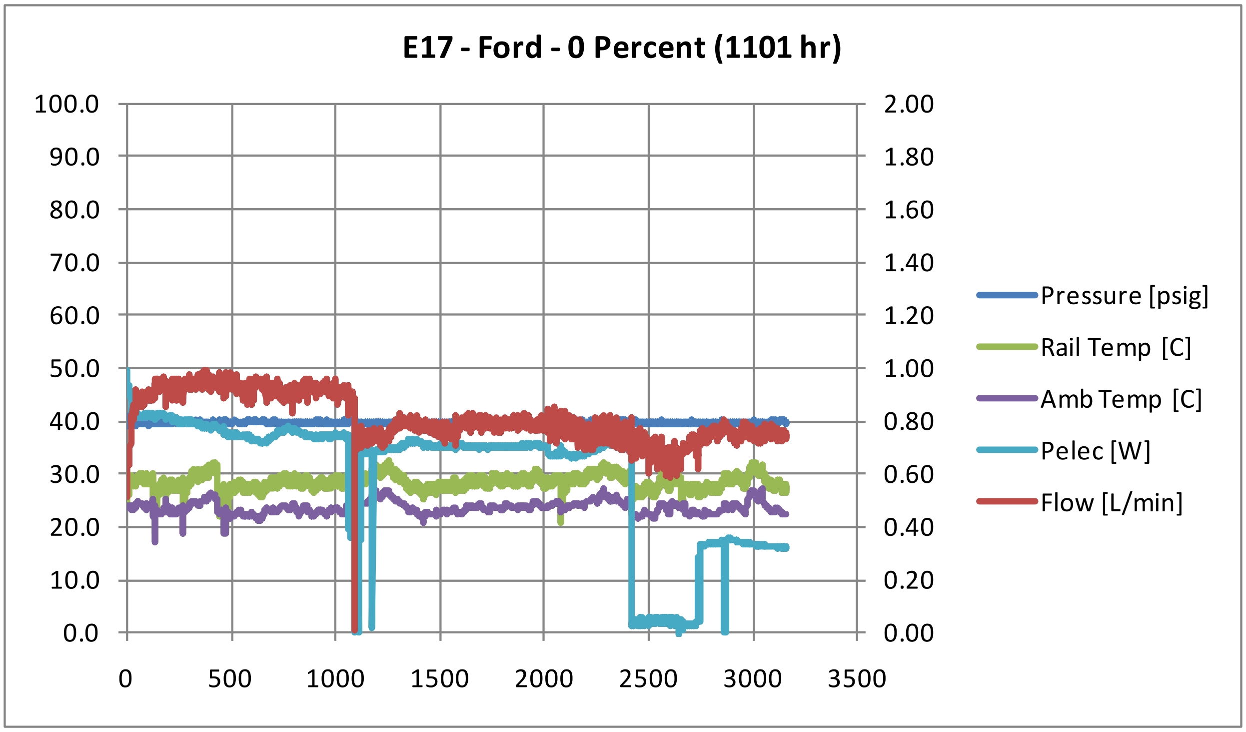

Figure B7: Ford E17- 0 percent fuel injector pulse width on (1,101 hr)

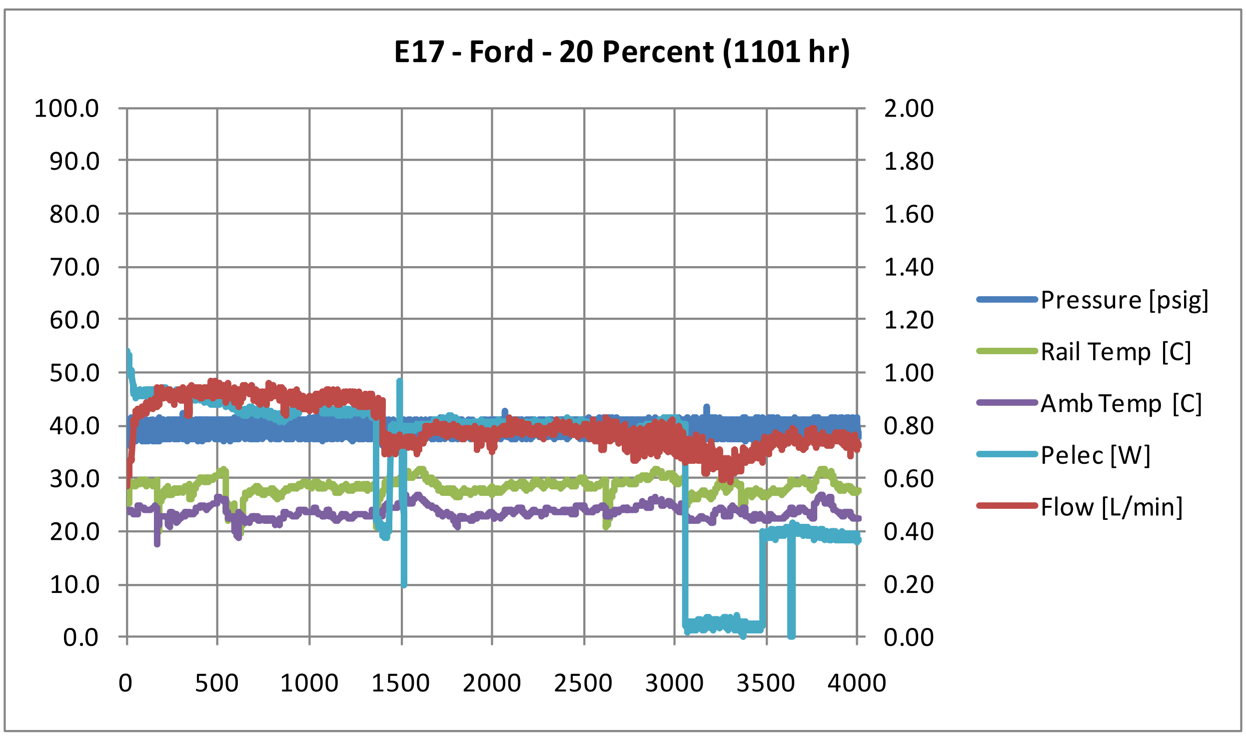

Figure B8: Ford E17 - 20 percent fuel injector pulse width on (1,101 hr)

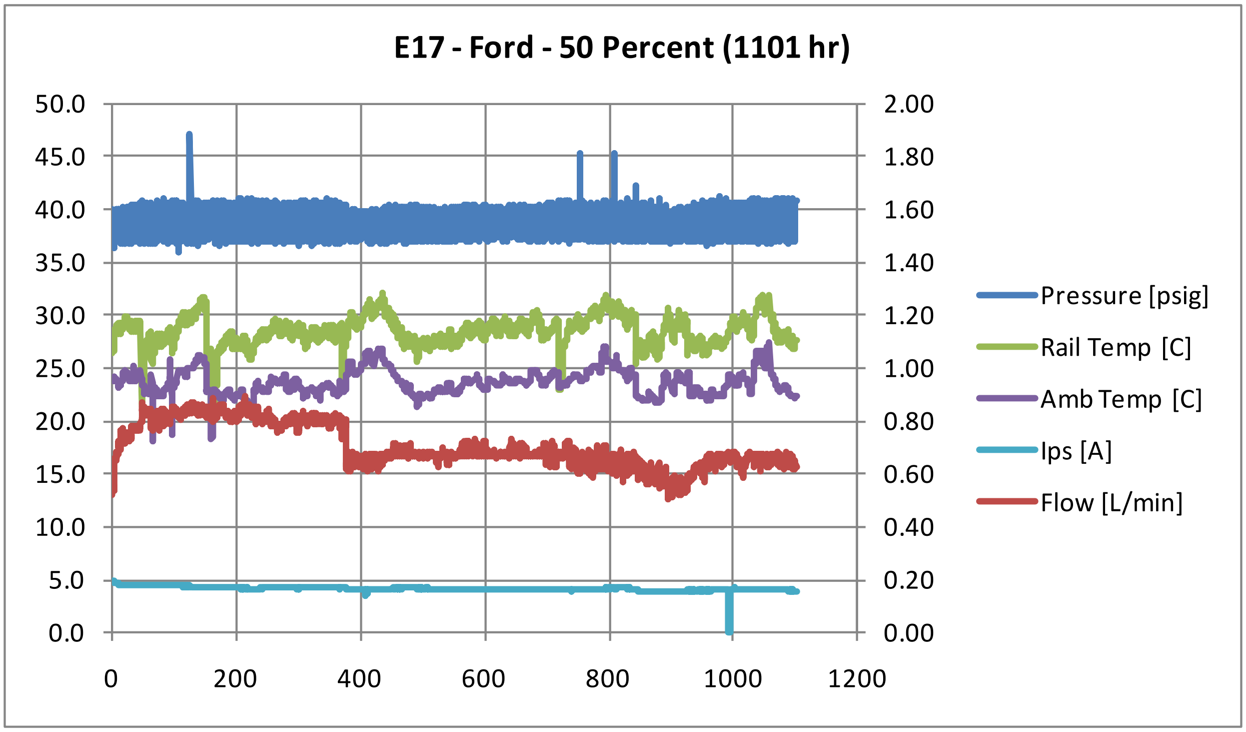

Figure B9: Ford E17 - 50 percent fuel injector pulse width on (1,101 hr)

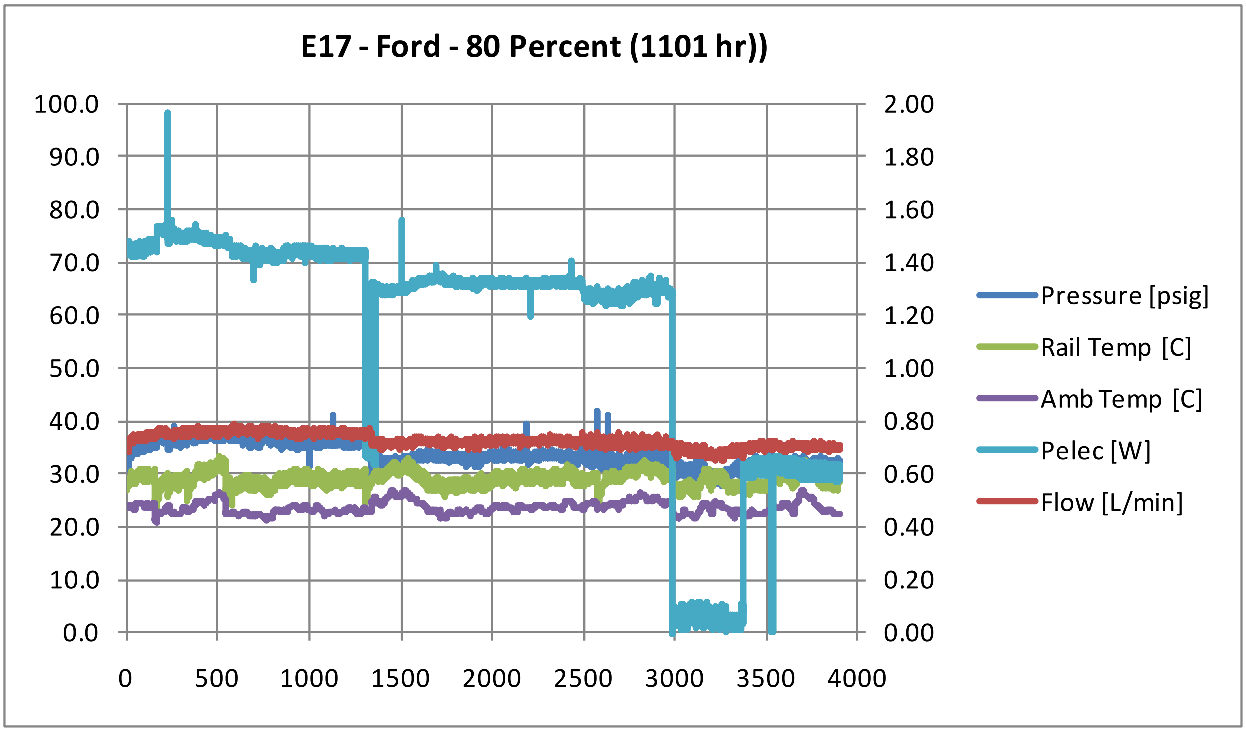

Figure B10: Ford E17 - 80 percent fuel injector pulse width on (1,101 hr)

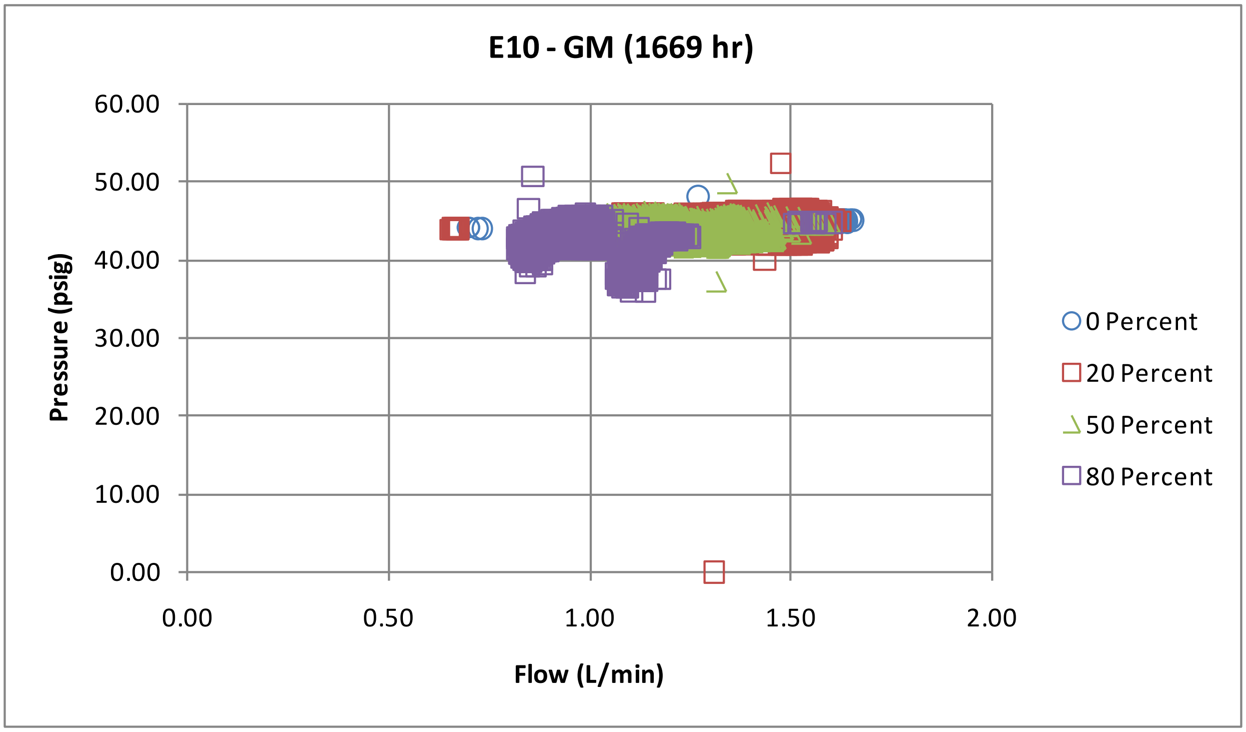

Figure B11: GM E10 pump operating conditions (1,669 hr)

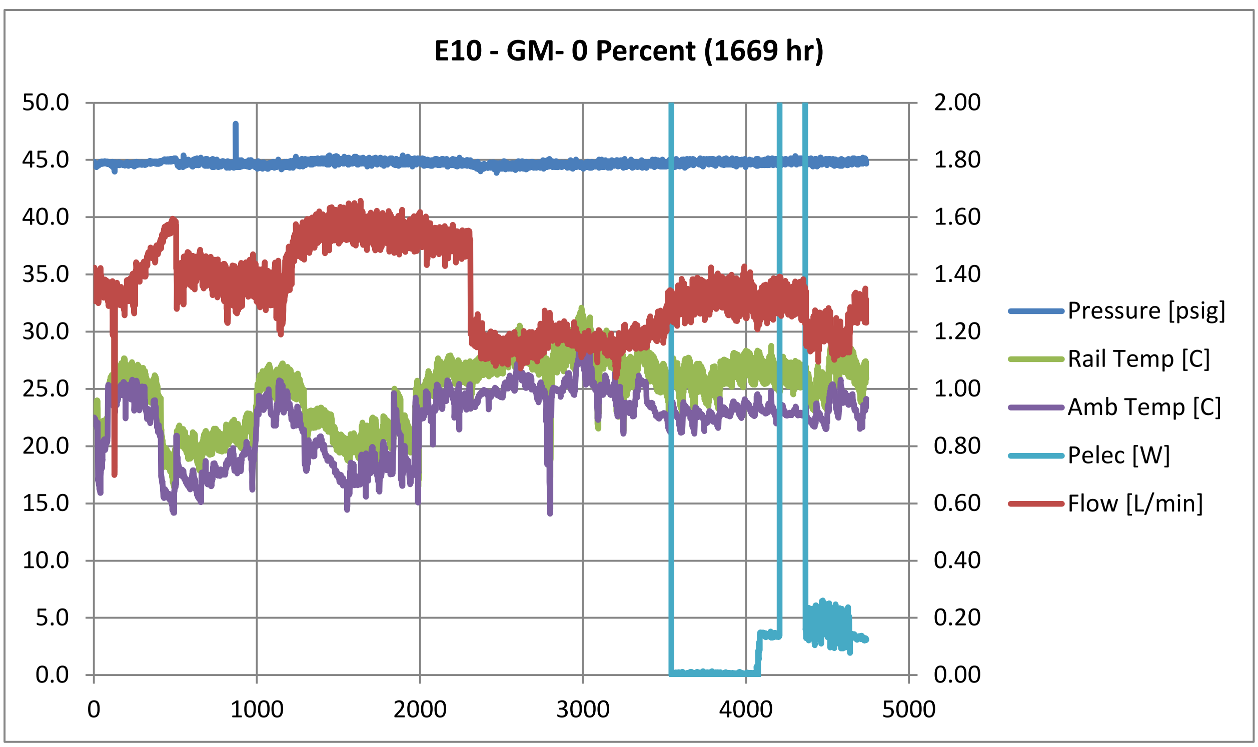

Figure B12: GM E10 - 0 percent fuel injector pulse width on (1,669 hr)

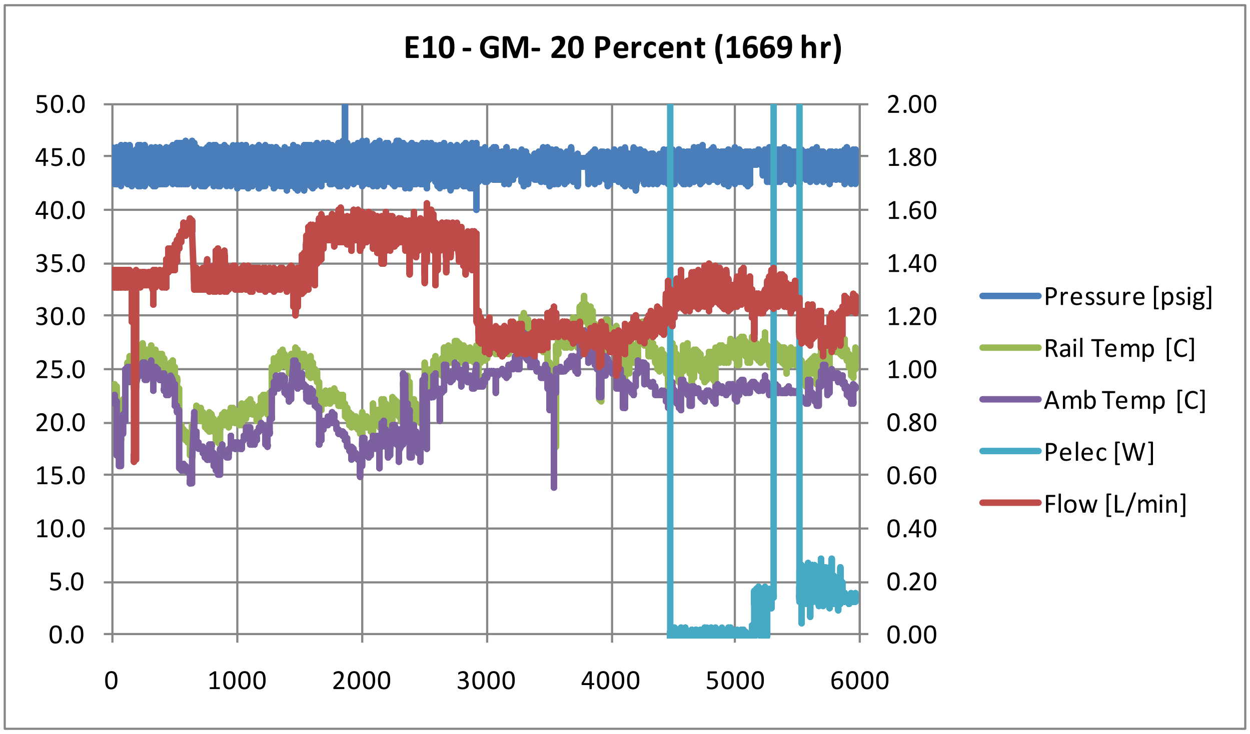

Figure B13: GM E10 - 20 percent fuel injector pulse width on (1,669 hr)

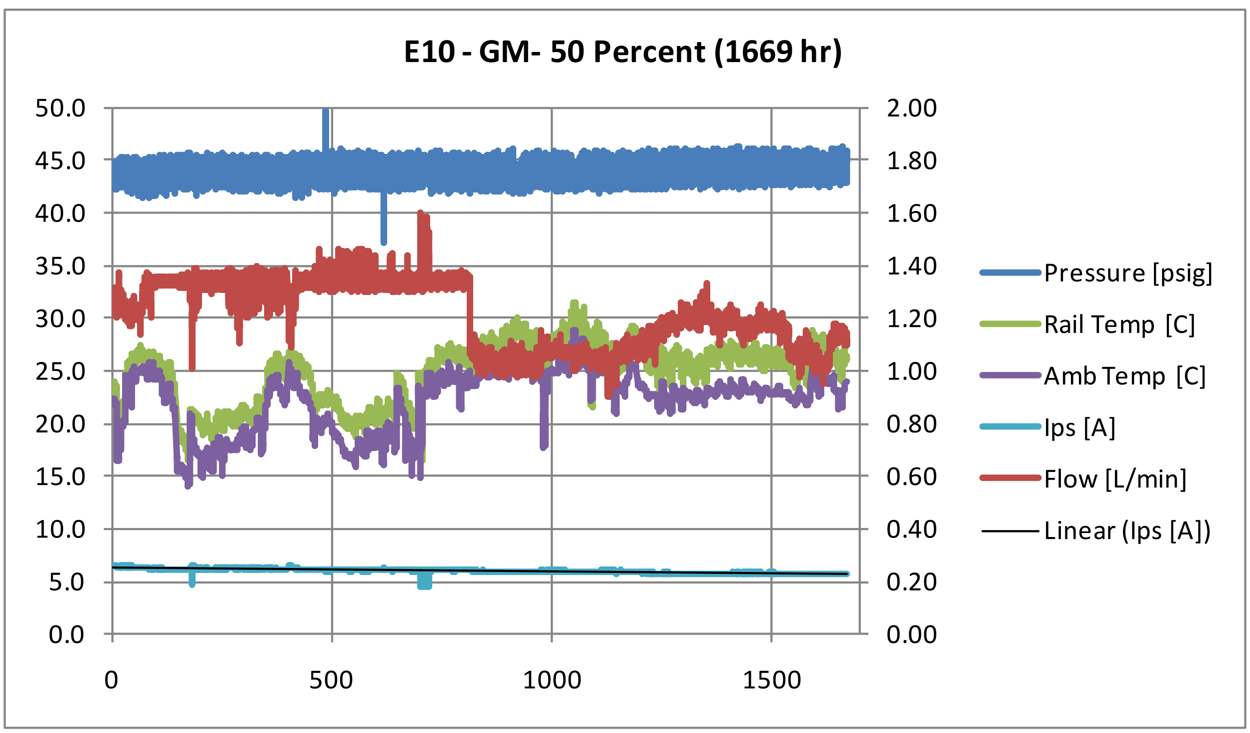

Figure B14: GM E10 - 50 percent fuel injector pulse width on (1,669 hr)

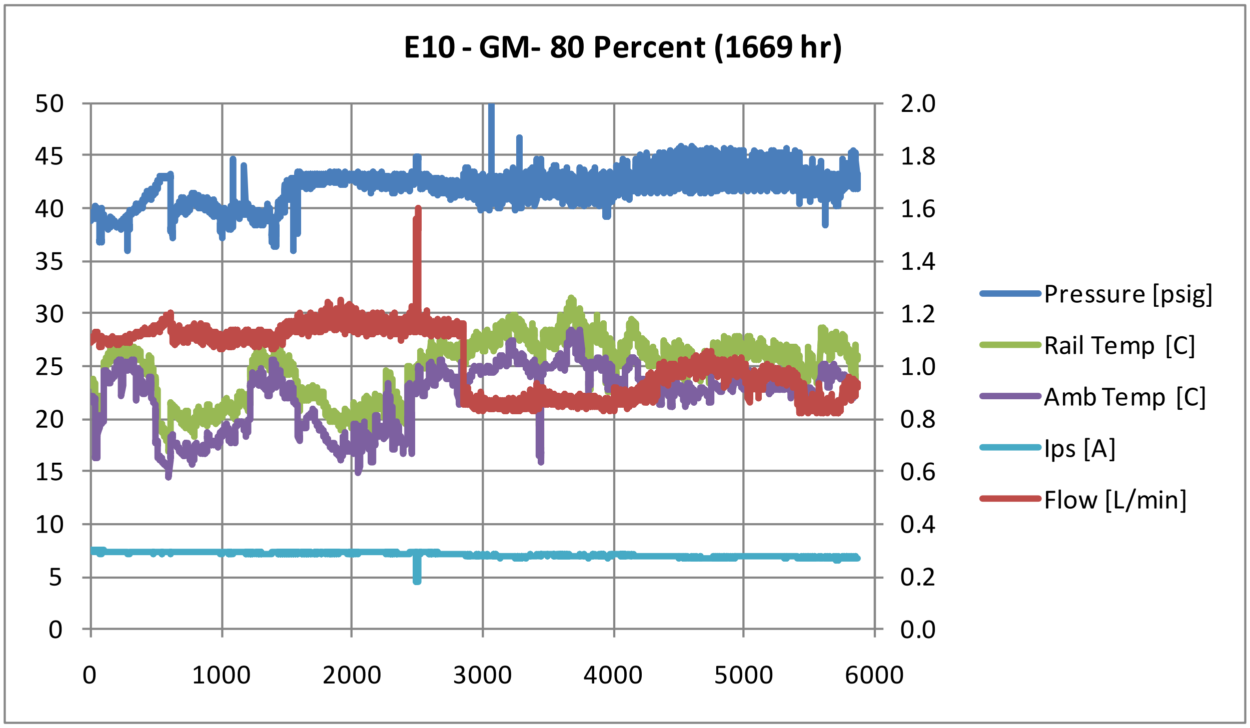

Figure B15: GM E10 - 80 percent fuel injector pulse width on (1,669 hr)

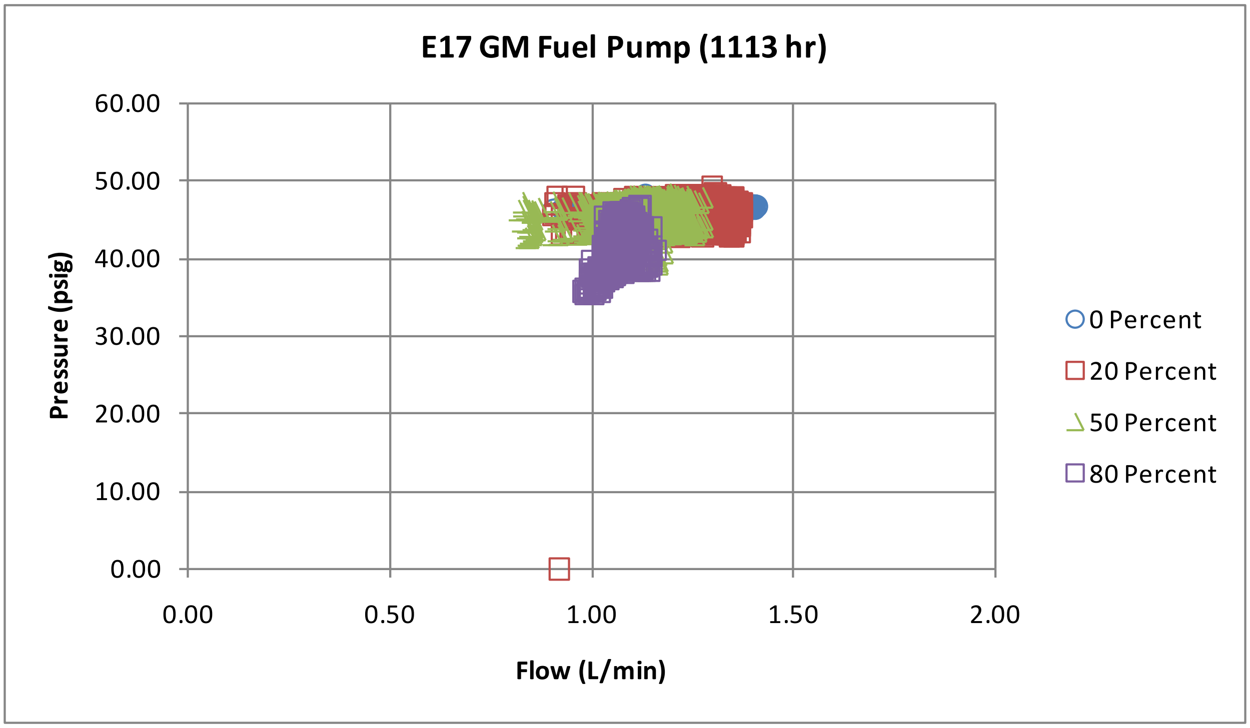

Figure B16: GM E17 pump operating conditions (1,113 hr)

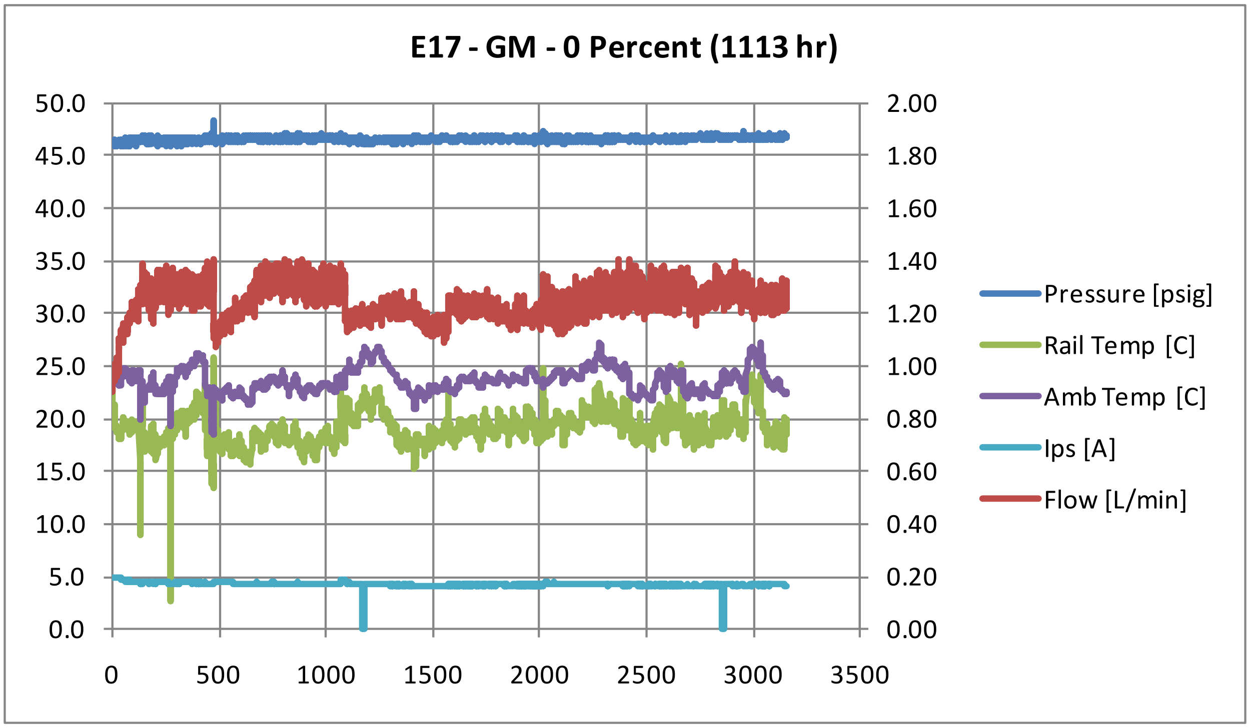

Figure B17: GM E17 - 0 percent fuel injector pulse width on (1,113 hr)

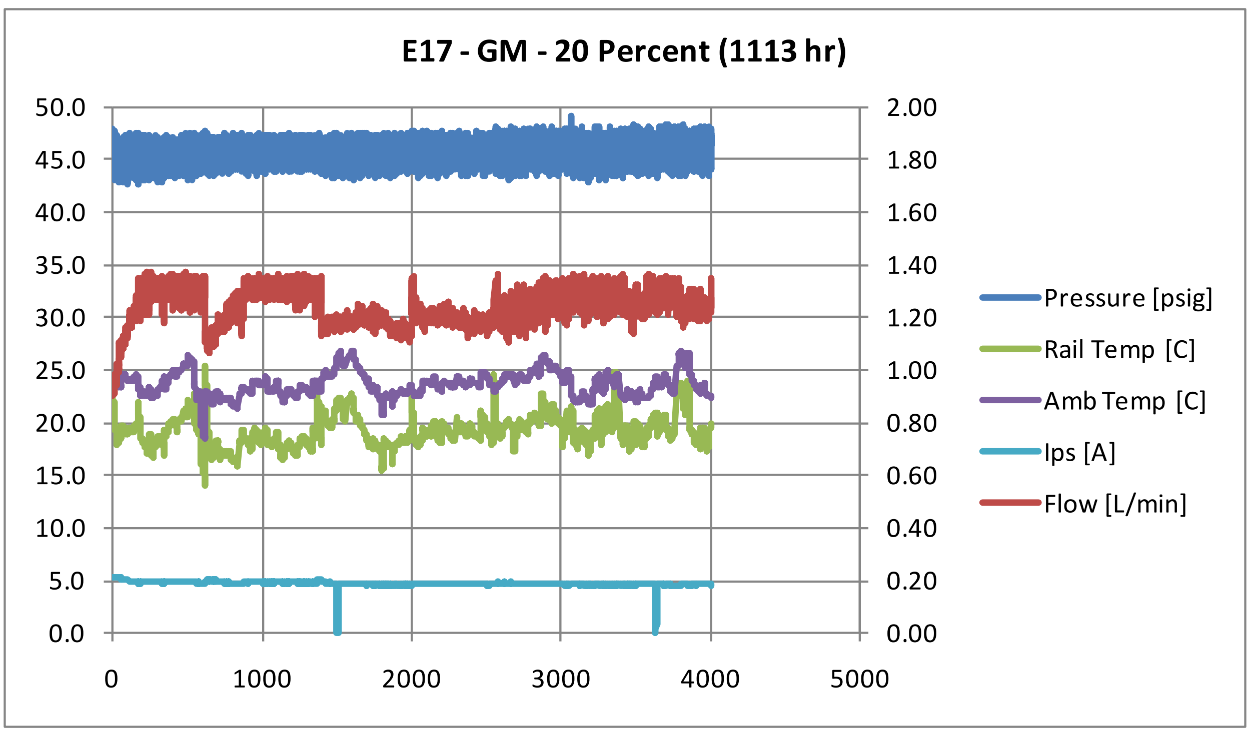

Figure B18: GM E17 - 20 percent fuel injector pulse width on (1,113 hr)

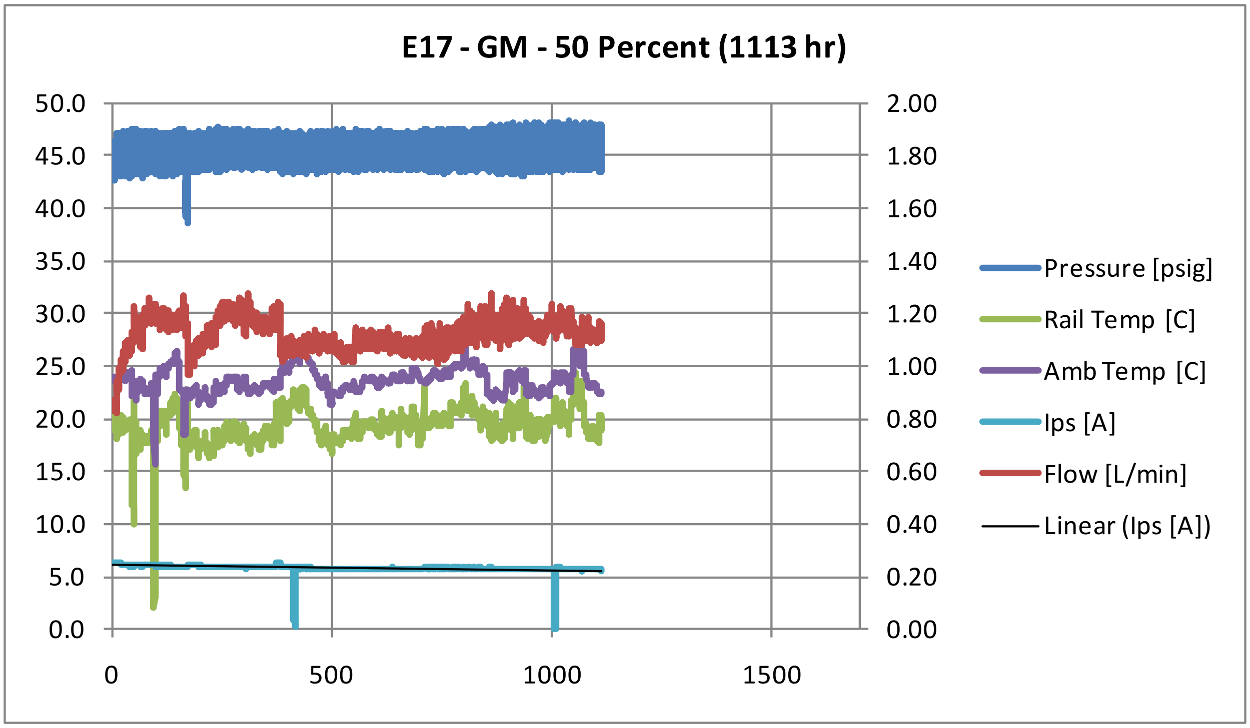

Figure B19: GM E17 - 50 percent fuel injector pulse width on (1,113 hr)

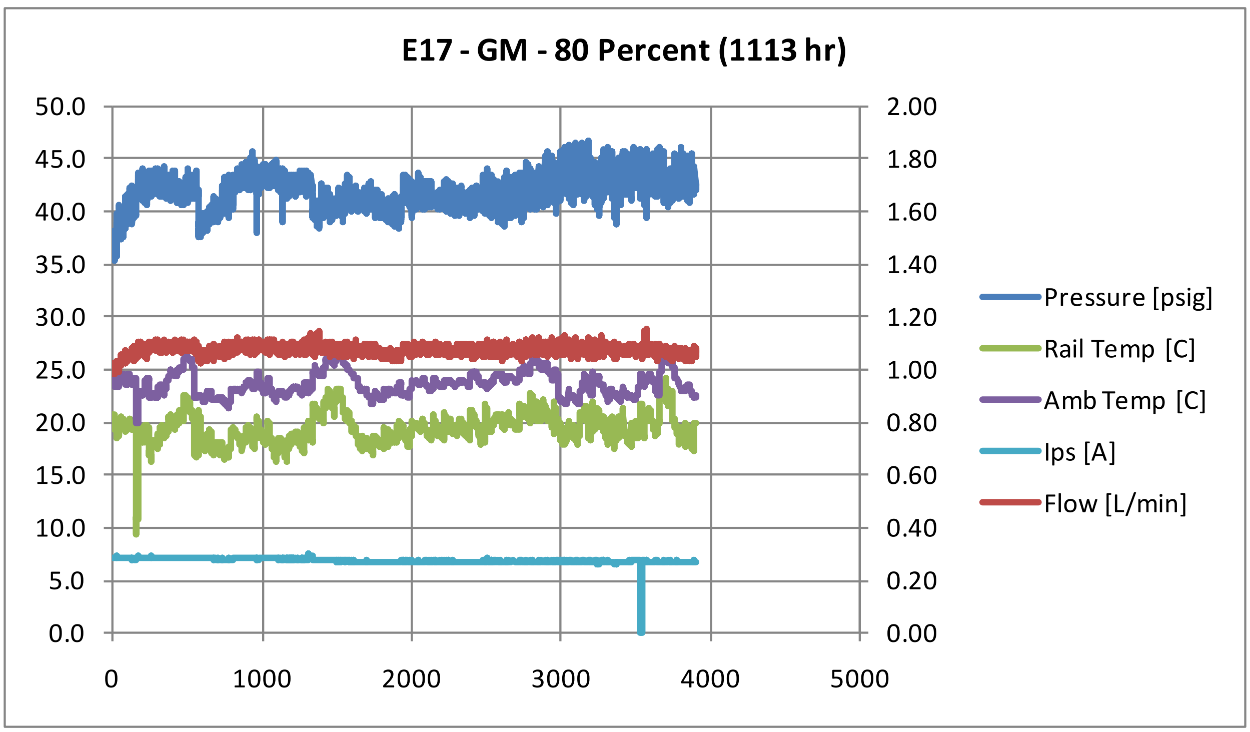

Figure B20: GM E17 - 80 percent fuel injector pulse width on (1,113 hr)

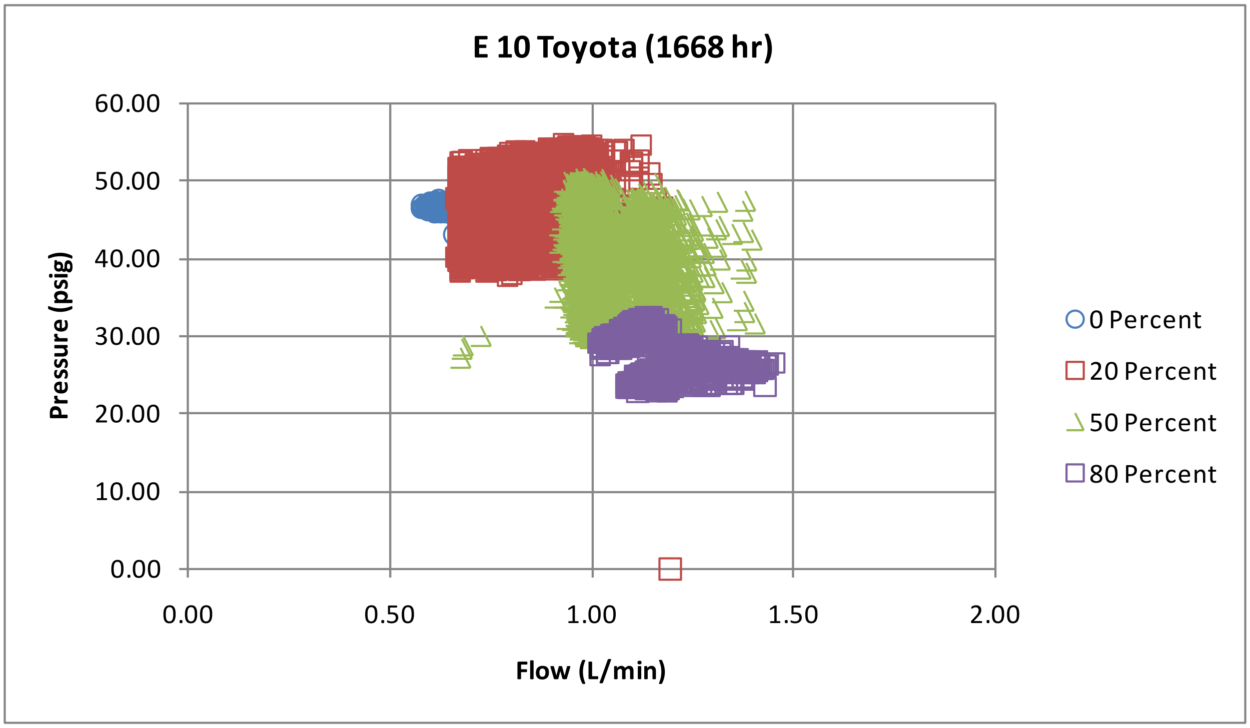

Figure B21: Toyota E10 pump operating conditions (1,668 hr)

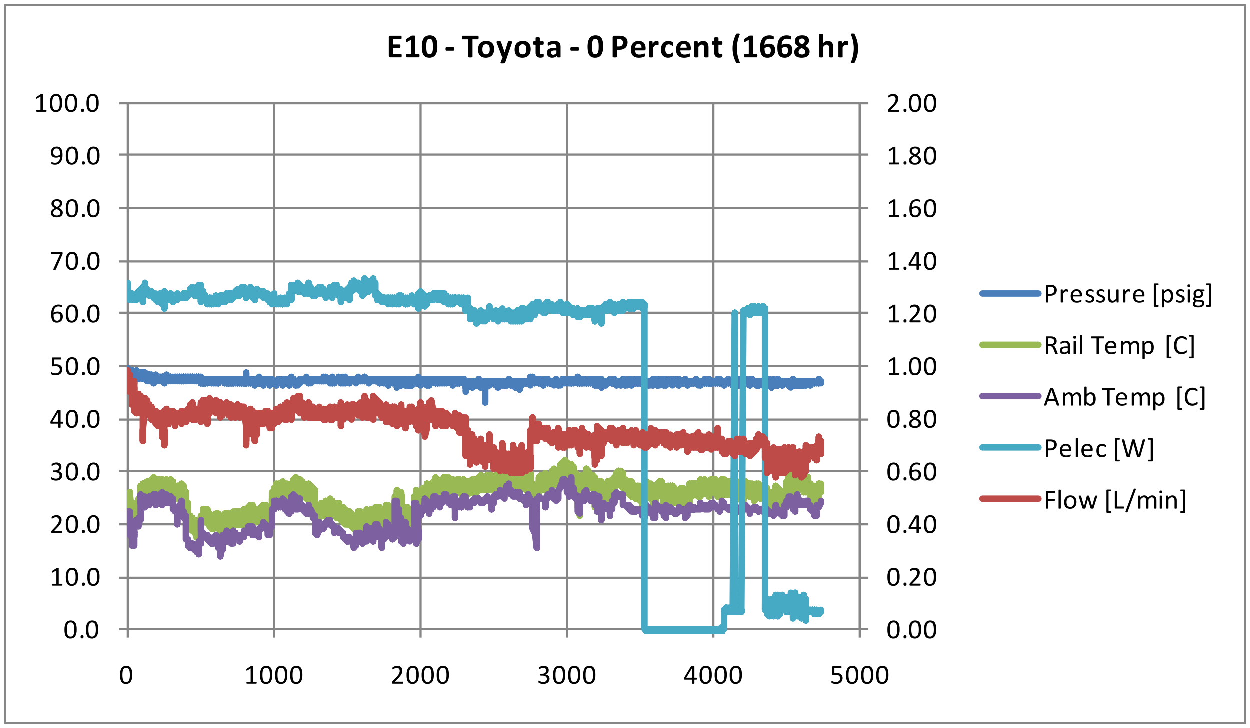

Figure B22: Toyota E10 - 0 percent fuel injector pulse width on (1,668 hr)

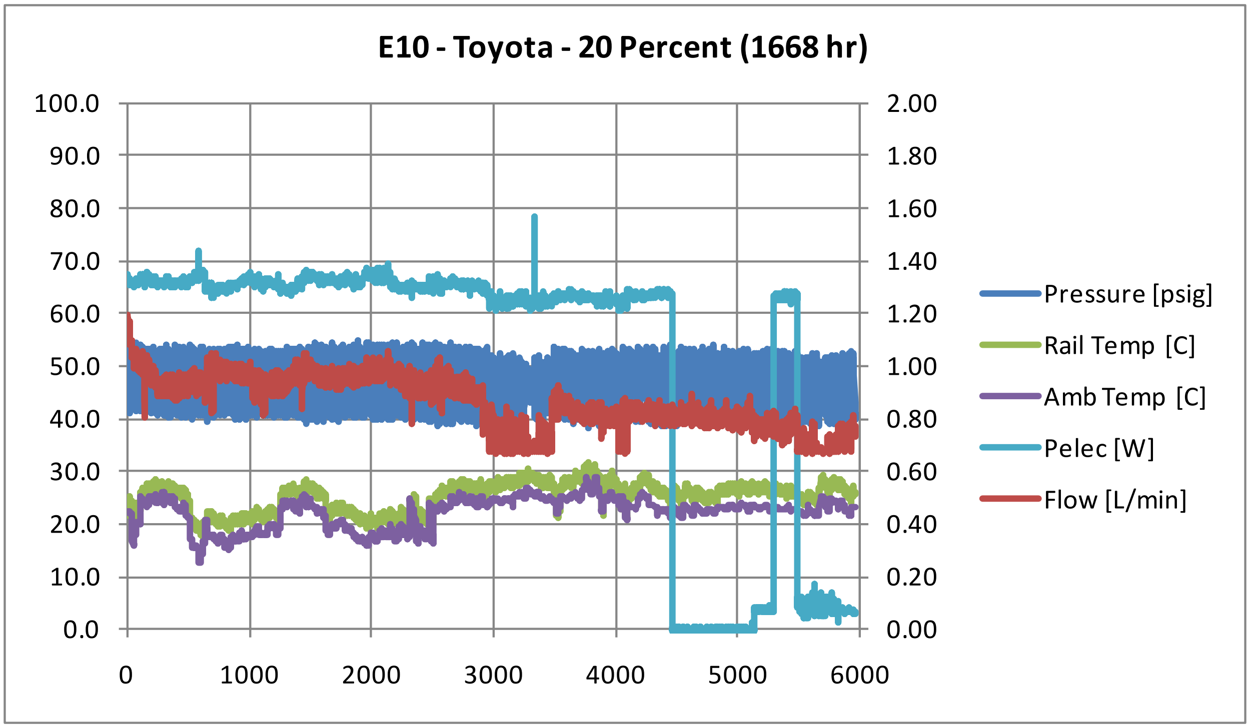

Figure B23: Toyota E10 - 20 percent fuel injector pulse width on (1,668 hr)

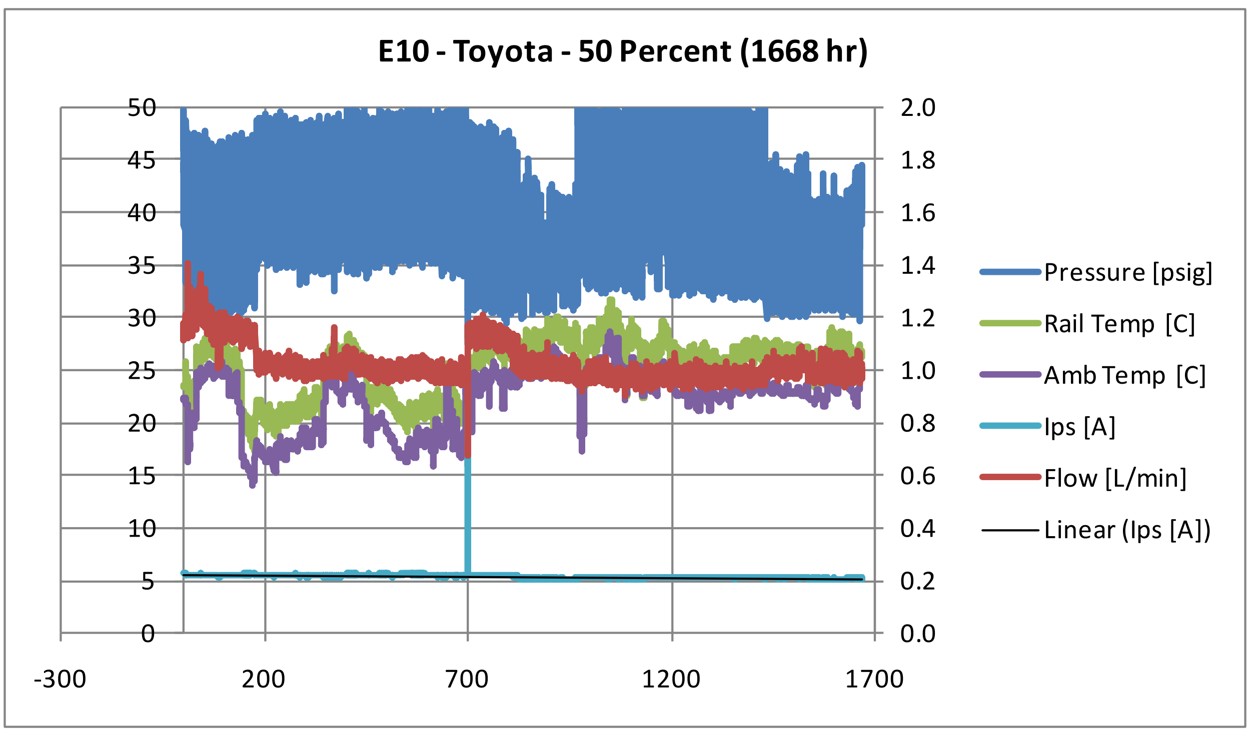

Figure B24: Toyota E10 - 50 percent fuel injector pulse width on (1,668 hr)

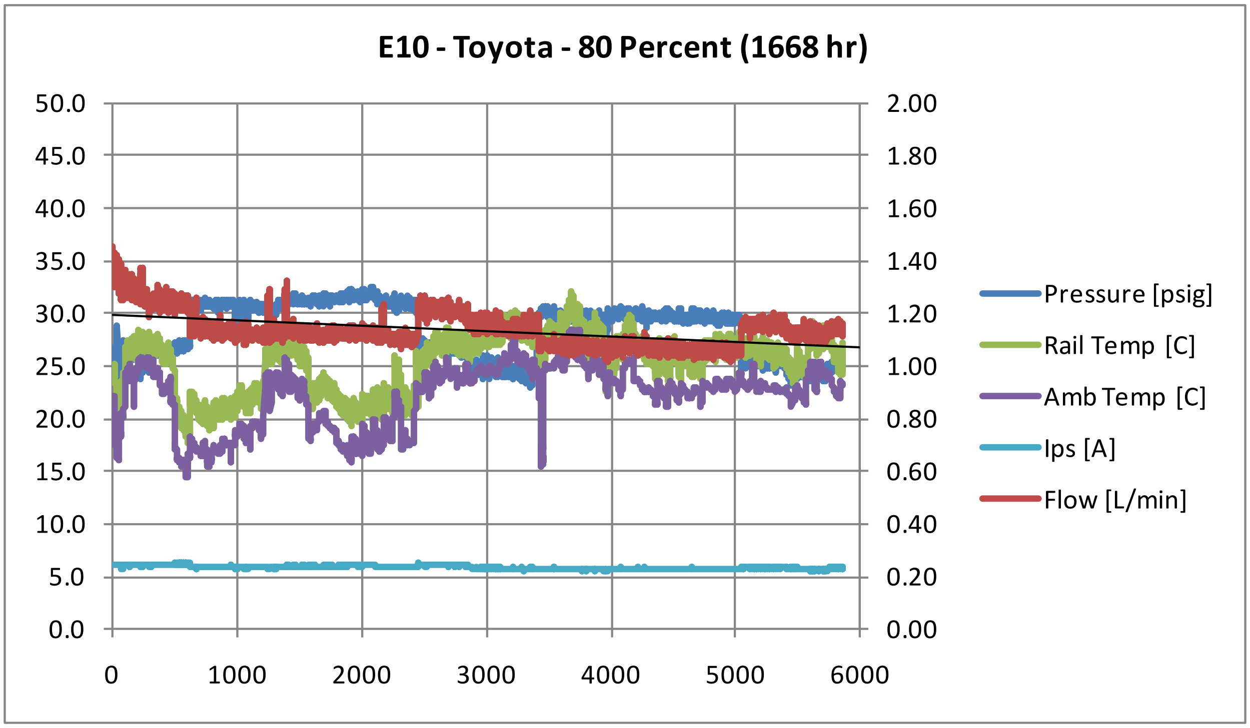

Figure B25: Toyota E10 - 80 percent fuel injector pulse width on (1,668 hr)

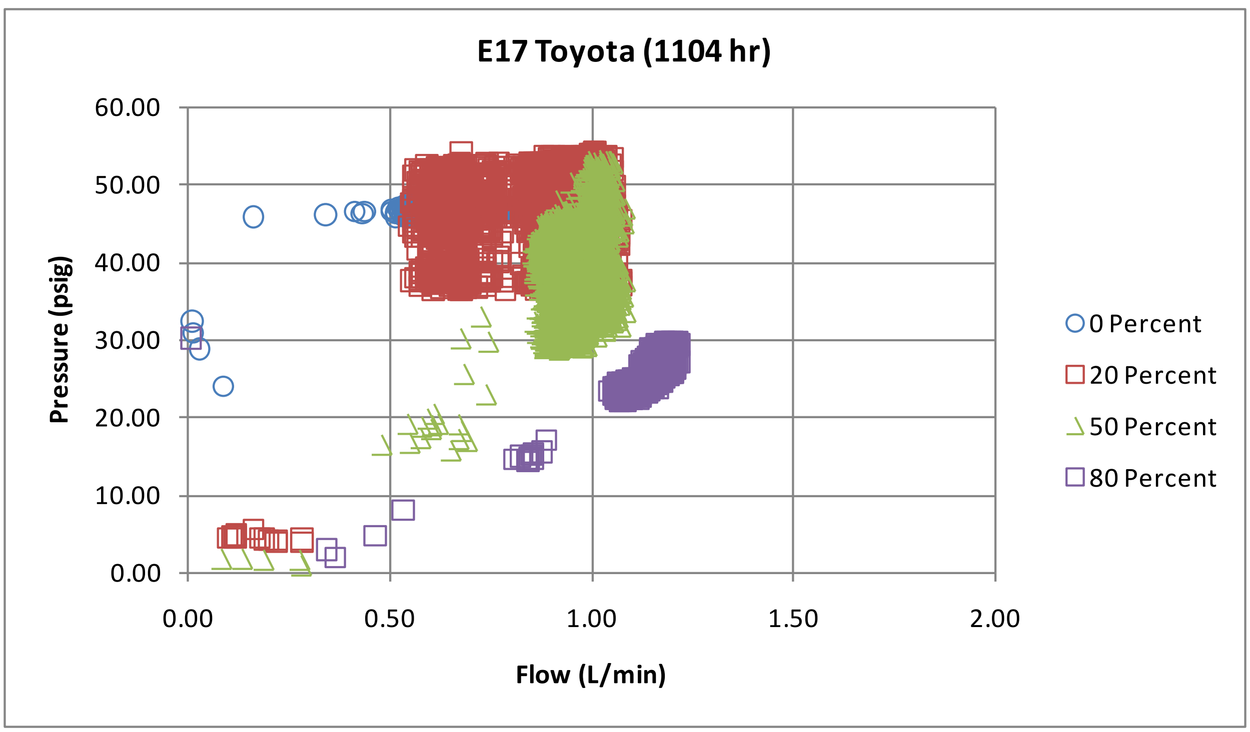

Figure B26: Toyota E17 pump operating conditions (1,104 hr)

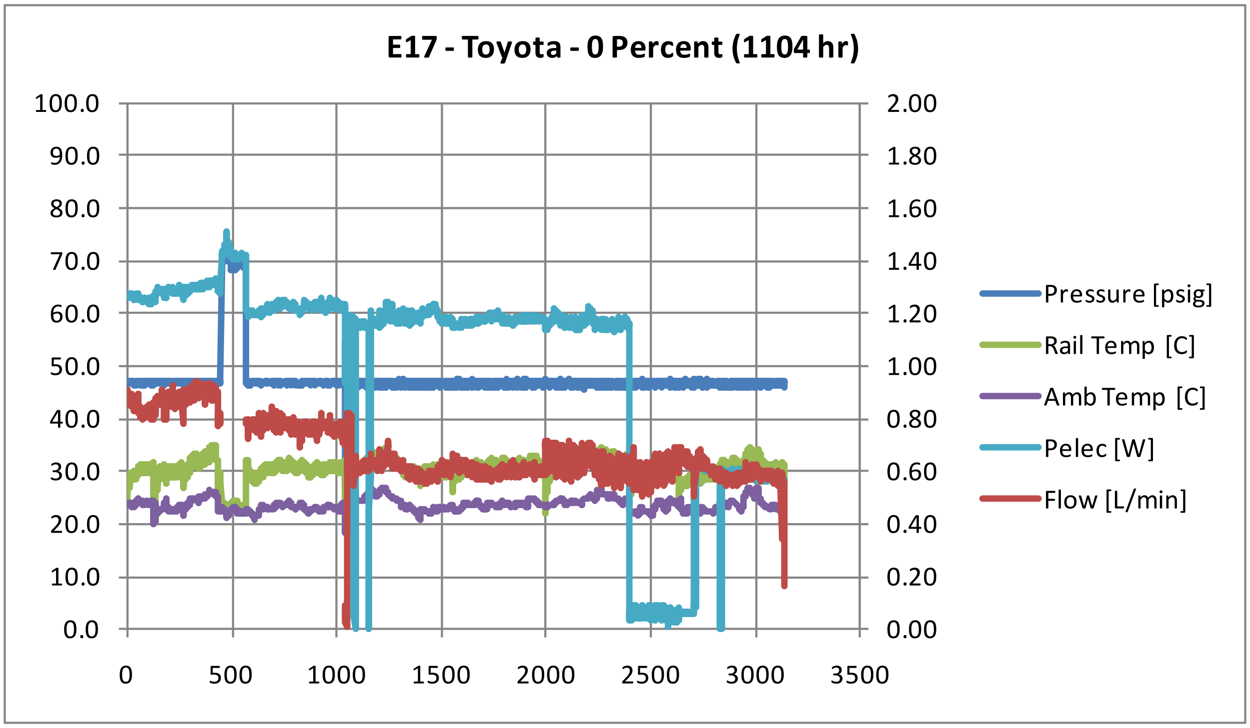

Figure B27: Toyota E17 - 0 percent fuel injector pulse width on (1,104 hr)

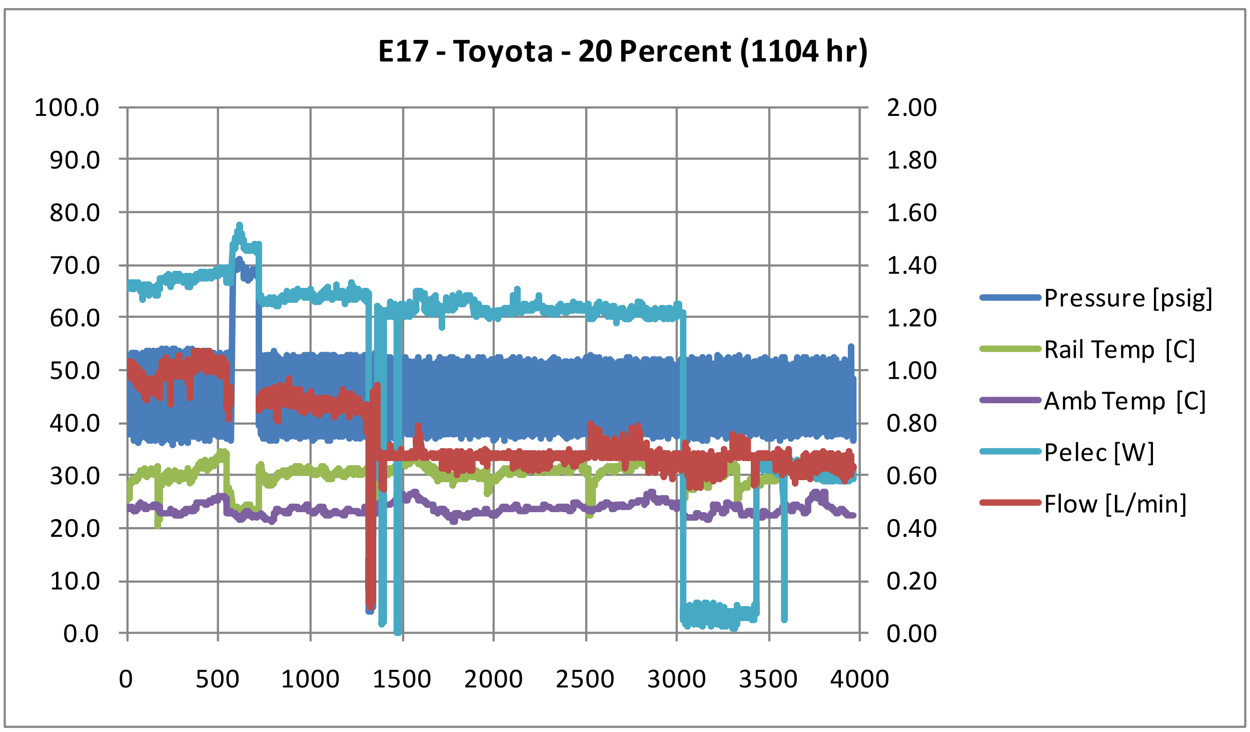

Figure B28: Toyota E17 - 20 percent fuel injector pulse width on (1,104 hr)

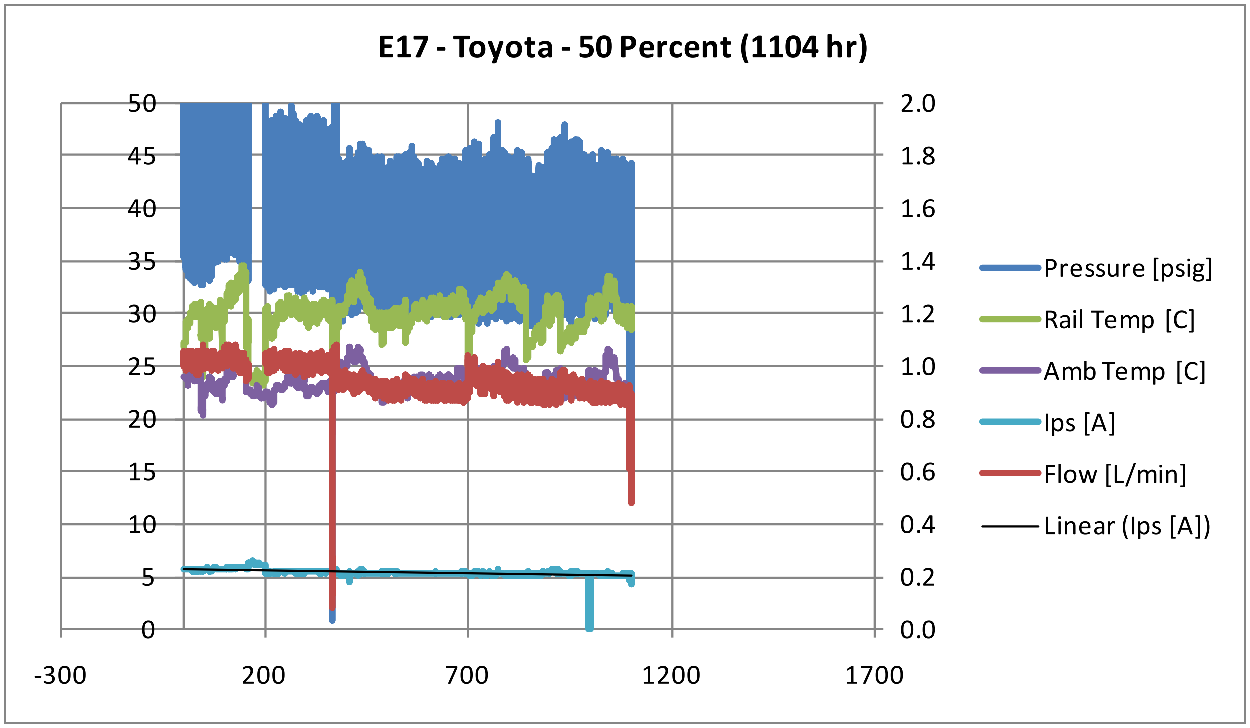

Figure B29: Toyota E17 - 50 percent fuel injector pulse width on (1,104 hr)

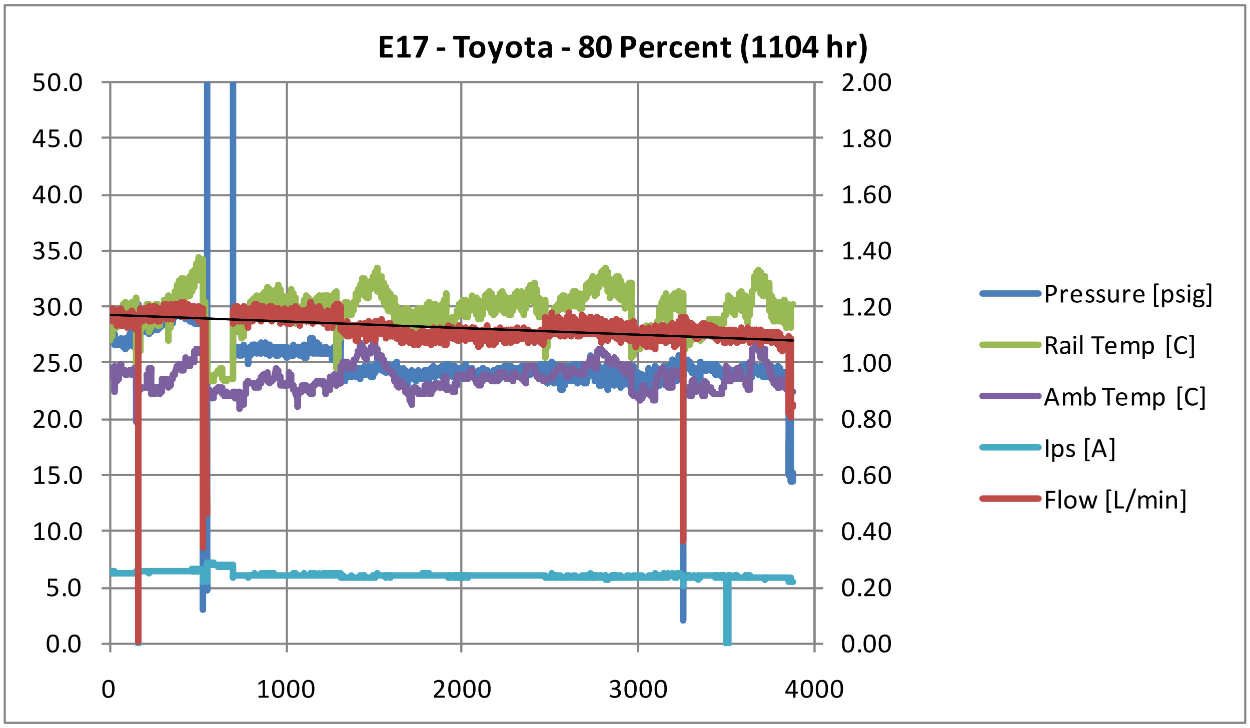

Figure B30: Toyota E17 - 80 percent fuel injector pulse width on (1,104 hr)

Appendix C

Procedures

The information provided in this appendix covers all the written test procedures. Only the complicated tasks and any task that was carried out by more than one person were written down. The first test procedure covers how to periodically test the fuel injectors. The second test procedure covers the pictures that were taken at the beginning and end of the experiment.

Fuel Injector Calibration Test Procedure

Introduction

All injectors need to be characterized before an experiment can begin. All injector testing will be conducted in accordance with SAE J1832, Low Pressure Gasoline Fuel Injector. The injectors will be calibrated in the fuel rail of each test system. Before testing, the pressure maintained in each fuel rail will be measured and verified. If a rail fails to maintain the proper pressure it will be replaced. If at some time a fuel injector should fail and a replacement fuel injector should be needed, it will initially be calibrated in the fuel rail in which it is going to be used for testing on. All fuel injector replacements will be noted, including the run time of the testing of the old injector prior to failure and the total system test time.

Testing (Note: color listings correspond to the attached table)

- Test fluid is mineral spirits. Density will be measured for each calibration test using the hydrometer (blue). (Remember: degree API = (141.5/SG) - 131.5, where SG is the fluid specific gravity.)
- First time only: Turn on fuel pump for approximately 15 min to soak the wetted parts and to check for any leaks. Measure and note the fuel rail pressure (turquoise).
- Pre-conditioning, first time only: Purge the fuel injectors by cycling 10,000 times at a 5 ms pulse width (PW). (This is a 50% duty cycle.)
- Watch to make sure the burettes do not overflow.
- Discard the purge fluid after use and before testing.
- Warm up: Cycle the injectors for 5,000 pulses at a period of 10 ms (100 Hz) and a pulse width of 5 ms (50% duty cycle).
- Estimate the flow rates and required number of cycles for ease in further testing.
- Dynamic Testing:
    - Drain the extra test fluid from burettes, and leave the level at the bottom starting mark (near 250 mL). Record the initial value.
    - Fire each injector at a 1, 2, 3, 4, 5, 6, 7, 8, and 9 ms PW using varying numbers of cycles (in increments of 1,000 cycles) aiming for 200 mL full (50 mL line) in the burettes.
    - Do not overflow burettes.
    - Record the final volume (or volume delivered) after each test, the number of cycles, and the pulse width.
    - Repeat test, starting at 9 ms, and proceeding down to 1 ms input data into spreadsheet (see example, fill in parts highlighted in red).
- Static Test: Conduct a static test for each injector by setting the pulse width to 10 ms while maintaining the period at 10 ms (100 % duty cycle)
    - Time the run for a volume of 200 mL (50 mL line)

    - The volume and time of injector should be recorded and inputted into the spreadsheet (see example, fill in parts highlighted in yellow)
- Post-Data Analysis:
    - Calculate the dynamic flow rate for each operating point
        - If the slope of the static flow rate is not close to the dynamic flow rates found above, fix issues and re-run the test
        - If any dynamic flow rate data pair deviates by more than 5%, re-run the operating point
    - Calculate the slope, time offset, and flow offset by performing a linear regression of the flow curve, using data points from 3,4, …,7 ms (see 4.1.10-4.1.13 SAE J1832)
    - Calculate the linear deviation (see 4.1.9 SAE J1832)
    - Calculate the Linear Flow Range of each injector (see 4.1.14 SAE J1832)
        - Using only the collected data, a coarse linear flow range can be calculated (see example, input the correct information into the area highlighted in pink). NOTE: For the initial and final testing, perform a more accurate determination by varying the PW in increments of 0.1 ms around the low flow and high flow limits of linearity.

Sample Fuel Injector Test Data/Analysis Sheet

Test 1 (Dec. 2 @ 2:00pm)							
pulse width (PW) (ms)	**Flow volume (ml)**	**# of Pulses**	**Flow volume per pulse (mL/pulse)**	**Flow mass per pulse Q.d (mg/pulse)**	**Dynamic Flow Rate Q (g/s)**	**Dynamic Flow Rate Calculated Qdc (g/s)**	**Linearity**
2	50	5000	0.0100	7.7361	0.7736	6.9315008	11.61%
2	50	5000	0.0100	7.7361	0.7736	6.9315008	11.61%
3	74	5000	0.0148	11.4494	1.1449	12.2539032	-6.57%
3	74	5000	0.0148	11.4494	1.1449	12.2539032	-6.57%
4	118	5000	0.0236	18.2571	1.8257	17.5763056	3.87%
4	118	5000	0.0236	18.2571	1.8257	17.5763056	3.87%
5	151	5000	0.0302	23.3629	2.3363	22.898708	2.03%
5	151	5000	0.0302	23.3629	2.3363	22.898708	2.03%
6	184	5000	0.0368	28.4687	2.8469	28.2211,104	0.88%
6	184	5000	0.0368	28.4687	2.8469	28.2211,104	0.88%
7	213	5000	0.0426	32.9556	3.2956	33.5435128	-1.75%
7	213	5000	0.0426	32.9556	3.2956	33.5435128	-1.75%

Specific Density of fluid	Density of fluid (g/L)
0.775	773.605

Fuel rail pressure (psi)	43

pulse width (PW) (ms)	Flow volume (ml)	# of Pulses	Flow volume per pulse (mL/pulse)	Flow mass per pulse Q.d (mg/pulse)	Dynamic Flow Rate Q (g/s)	Dynamic Flow Rate Calculated Qdc (g/s)	Linearity
8	204	4000	0.0510	39.4539	3.9454	38.8659152	1.51%
8	204	4000	0.0510	39.4539	3.9454	38.8659152	1.51%
9	180	3000	0.0600	46.4163	4.6416	44.1883176	5.04%
9	180	3000	0.0600	46.4163	4.6416	44.1883176	5.04%

	ml	sec	ml/s	-	Q.s (g/s)
Static flow rate	205	30	6.8333	-	5.2863

Least Sq regression	Slope	5.3224024	Intercept	-3.713304	
Slope (m)	5.3224024	mg/ms			
X offset (time offset)	0.697674419	ms/pulse		LFR=	2.161016949
Y offset (flow offset)	-3.713304	mg/pulse			

Photograph procedure

Fuel injector pictures

- Overview picture with name plate
- Side view picture
- Strait on view of fuel injector rail side
- ISO view of fuel injector rail side
- Strait on view of spray side
- ISO view of spray side
- Other pictures as necessary

Fuel Rail

- Overview picture with name plate
- One picture showing each hole (6 pictures)
- Side view showing each end (2 pictures)
- Regulator picture
- Other pictures as necessary

Fuel Sending Unit

- Overview picture with name plate
- Picture of fuel pump
- Picture of fuel sock
- Picture showing each inlet/outlet hole
- Other pictures as necessary

Appendix D

Fuel Samples

The information provided in this appendix covers the test results of the fuel samples, which were analyzed by Southwest Research Institute.

Ford

Sample Code			E10	E17	F-10 2-19-11	F-10 4/4/11	F17 5-2-11	F-17 5-25-11	F-17 06-02-11
Time On Fuel		Hours	0	0	196	430	216	334	147
Time on System		Hours			196	853	385	720	867
D5191	RVP	psi	10.98	11.92	9.99	9.97	9.1	8.95	10.63
D130	Copper		1a	1a	1a	1a	1a	1A	1A
D1613	Acidity	mg KOH/g	0.0129	0.0091	0.0226	0.0154	0.0149	0.0164	0.0121
D2624	EConduct	pS/m	>1999	>1999	1999	>1999	1999	>1999	>1999
	Temperat	deg C	1	1	8.8	3	19	14.5	2
D3703	Peroxide	mg/kg	0.6842	0.9118	0.6828	1.4853	0.4567	0	0
D381	UnWshdGm		17.5	17.5	81	54.5	60.5	58	30.5
	WashdGum		1	0.5	23	23.5	32	25	13
D4176	ClrBrt		C&B	C&B	C&B	C&B	C&B	C&B	C&B
	Particul		no	no	no	no	no	no	no
	FreeWatr		no	no	no	no	no	no	no
	Haze		1	1	1	1	1	1	1
D5185	Al	ppm	<1	<1	<1	<1	<1	<1	<1
	Sb	ppm	<1	<1	<1	<1	<1	<1	<1
	Ba	ppm	<1	<1	<1	<1	<1	<1	<1
	B	ppm	0.2	<1	<1	<1	<1	0.6	<1
	Ca	ppm	<1	<1	<1	<1	<1	<1	<1
	Cr	ppm	<1	<1	<1	<1	<1	<1	<1
	Cu	ppm	<1	<1	0.6	0.4	0.2	0.4	0.4
	Fe	ppm	0.2	<1	<1	<1	<1	<1	<1
	Pb	ppm	<1	<1	<1	<1	<1	<1	<1
	Mg	ppm	<1	<1	<1	<1	<1	<1	<1
	Mn	ppm	<1	<1	<1	<1	<1	<1	<1
	Mo	ppm	<1	<1	<1	<1	<1	<1	<1
	Ni	ppm	<1	<1	<1	<1	<1	<1	<1
	P	ppm	<1	<1	<1	<1	<1	<1	<1
	Si	ppm	<1	<1	<1	<1	<1	<1	<1
	Ag	ppm	<1	<1	<1	<1	<1	<1	<1
	Na	ppm	<5	<5	<5	<5	<5	<5	<5
	Sn	ppm	<1	<1	1	0.4	0.4	0.4	<1
	Zn	ppm	0.4	<1	0.4	0.2	0.2	0.2	0.4
	K	ppm	<5	<5	<5	<5	<5	<5	<5
	Sr	ppm	<1	<1	<1	<1	<1	<1	<1
	V	ppm	<1	<1	<1	<1	<1	<1	<1
	Ti	ppm	<1	<1	<1	<1	<1	<1	<1
	Cd	ppm	<1	<1	<1	<1	<1	<1	<1
D5188	V/L=20	degF	120.5	117.3	126.4	142.4	131.4	133.2	123.3
D525	RunTime	min	1440	1440	1440	1440	1440	1440	1440
	BreakY/N		NO BREAK	NO BREAK	NO BREAK	NO BREAK	NO BREAK	NO BREAK	NO BREAK
	BreakPt	min	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	psiDrop	psi	89.1	43.8	50.8	91.9	20.3	13	15.2
D5453	Sulfur	ppm	36.4	30.5					
D5599	EtOHVol	Vol%	10.5301	19.5537	9.5913	10.5506	20.1244	18.3577	15.4345
	EtOHWt	Wt%	11.3262	20.9893	10.2264	10.9649	21.2712	19.3883	16.4985
	EtOHVol	Vol%	10.4041	19.5023					
	EtOHWt	Wt%	11.1906	20.9341					
	EtOHVol	Vol%	10.3447	19.4049					
	EtOHWt	Wt%	11.1268	20.8296					
D6304	Water%	%	0.10506	0.23252	0.0923	0.09127	0.23612	0.24468	0.1975
	WaterPPM	ppm	1051	2325	923	913	2361	2447	1975
D7328	TChlorid	ppm	0	0	0	0	0	0	0
	TSulfate	ppm	0.4	0	0	0	0	0	0
	PSulfate	ppm	0.5	0.2	0.2	0	0.4	0	0.2

GM

Sample Code			E10	E17	G-10 2-19-11	G-10 4/4/11	G17 5-2-11	G-17 5-25-11	G-17 06-02-11
Time On Fuel		Hours	0	0	196	430	216	334	147
Time on System		Hours			196	853	385	720	867
D5191	RVP	psi	10.98	11.92	10.32	9.45	7.31	9.13	9.18
D130	Copper		1a	1a	1a	1a	1a	1A	1A
D1613	Acidity	mg KOH/g	0.0129	0.0091	0.0242	0.0144	0.017	0.0166	0.0127
D2624	EConduct	pS/m	>1999	>1999	1999	>1999	1999	>1999	>1999
	Temperat	deg C	1	1	7.8	3	19	14.5	2
D3703	Peroxide	mg/kg	0.6842	0.9118	1.1418	1.3705	0.4571	0	0
D381	UnWshdGm		17.5	17.5	124	72	106	60	39
	WashdGum		1	0.5	13.5	36	55	21	9
D4176	ClrBrt		C&B	C&B	C&B	C&B	C&B	C&B	C&B
	Particul		no	no	no	no	no	no	no
	FreeWatr		no	no	no	no	no	no	no
	Haze		1	1	1	1	1	1	1
D5185	Al	ppm	<1	<1	<1	<1	<1	<1	<1
	Sb	ppm	<1	<1	<1	<1	<1	<1	<1
	Ba	ppm	<1	<1	<1	<1	<1	<1	<1
	B	ppm	0.2	<1	0.2	<1	<1	0.4	<1
	Ca	ppm	<1	<1	<1	<1	<1	<1	<1
	Cr	ppm	<1	<1	<1	<1	<1	<1	<1
	Cu	ppm	<1	<1	0.4	0.4	<1	0.4	0.4
	Fe	ppm	0.2	<1	<1	<1	<1	<1	<1
	Pb	ppm	<1	<1	<1	<1	<1	<1	<1
	Mg	ppm	<1	<1	<1	<1	<1	<1	<1
	Mn	ppm	<1	<1	<1	<1	<1	<1	<1
	Mo	ppm	<1	<1	<1	<1	<1	<1	<1
	Ni	ppm	<1	<1	<1	<1	<1	<1	<1
	P	ppm	<1	<1	<1	<1	<1	<1	<1
	Si	ppm	<1	<1	1	<1	<1	<1	0.4
	Ag	ppm	<1	<1	<1	<1	<1	<1	<1
	Na	ppm	<5	<5	<5	<5	<5	<5	<5
	Sn	ppm	<1	<1	1.4	0.6	0.8	0.4	<1
	Zn	ppm	0.4	<1	<1	0.2	<1	<1	<1
	K	ppm	<5	<5	<5	<5	<5	<5	<5
	Sr	ppm	<1	<1	<1	<1	<1	<1	<1
	V	ppm	<1	<1	<1	<1	<1	<1	<1
	Ti	ppm	<1	<1	<1	<1	<1	<1	<1
	Cd	ppm	<1	<1	<1	<1	<1	<1	<1
D5188	V/L=20	degF	120.5	117.3	123.7	148.5	141.2	131.5	131.3
D525	RunTime	min	1440	1440	1440	1440	1440	1440	1440
	BreakY/N		NO BREAK	NO BREAK	NO BREAK	NO BREAK	NO BREAK	NO BREAK	NO BREAK
	BreakPt	min	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	psiDrop	psi	89.1	43.8	57.1	45.7	21.3	19	51.5
D5453	Sulfur	ppm	36.4	30.5					
D5599	EtOHVol	Vol%	10.5301	19.5537	8.8703	7.9778	21.1032	16.2675	15.6258
	EtOHWt	Wt%	11.3262	20.9893	9.5061	8.1502	22.0329	17.2197	16.5648
	EtOHVol	Vol%	10.4041	19.5023					
	EtOHWt	Wt%	11.1906	20.9341					
	EtOHVol	Vol%	10.3447	19.4049					
	EtOHWt	Wt%	11.1268	20.8296					
D6304	Water%	%	0.10506	0.23252	0.089	0.07448	0.27866	0.2152	0.18306
	WaterPPM	ppm	1051	2325	890	745	2787	2152	1831
D7328	TChlorid	ppm	0	0	0	0	0	0	0
	TSulfate	ppm	0.4	0	0	0	0.2	2	0
	PSulfate	ppm	0.5	0.2	0.2	0.3	0.3	0.7	0.3

Toyota

Sample Code			E10	E17	T-10 2-19-11	T-10 4/4/11	T17 5-2-11	T-17 5-25-11	T-17 06-02-11
Time On Fuel		Hours	0	0	196	430	216	334	147
Time on System		Hours			196	853	385	720	867
D5191	RVP	psi	10.98	11.92	5.97	5.71	8.38	4.02	6.03
D130	Copper		1a	1a	1a	1a	1a	1A	1A
D1613	Acidity	mg KOH/g	0.0129	0.0091	0.0344	0.0205	0.0126	0.0199	0.0183
D2624	EConduct	pS/m	>1999	>1999	1999	>1999	1999	>1999	>1999
	Temperat	deg C	1	1	8.2	3	19	14.5	2
D3703	Peroxide	mg/kg	0.6842	0.9118	1.3662	1.7125	0.5713	0.6834	0.5703
D381	UnWshdGm		17.5	17.5	142.5	90	55.5	95.5	42
	WashdGum		1	0.5	13	17.5	9.5	60	6.5
D4176	ClrBrt		C&B	C&B	C&B	C&B	C&B	C&B	C&B
	Particul		no	no	no	no	no	no	no
	FreeWatr		no	no	no	no	no	no	no
	Haze		1	1	1	1	1	1	1
D5185	Al	ppm	<1	<1	<1	<1	<1	<1	<1
	Sb	ppm	<1	<1	<1	<1	<1	<1	<1
	Ba	ppm	<1	<1	<1	<1	<1	<1	<1
	B	ppm	0.2	<1	0.4	<1	0.4	0.4	<1
	Ca	ppm	<1	<1	<1	<1	<1	<1	<1
	Cr	ppm	<1	<1	<1	<1	<1	<1	<1
	Cu	ppm	<1	<1	0.6	1.2	0.4	1.6	0.8
	Fe	ppm	0.2	<1	<1	<1	<1	<1	<1
	Pb	ppm	<1	<1	<1	<1	<1	<1	<1
	Mg	ppm	<1	<1	<1	<1	<1	<1	<1
	Mn	ppm	<1	<1	<1	<1	<1	<1	<1
	Mo	ppm	<1	<1	<1	<1	<1	<1	<1
	Ni	ppm	<1	<1	<1	<1	<1	<1	<1
	P	ppm	<1	<1	<1	<1	<1	<1	<1
	Si	ppm	<1	<1	<1	<1	<1	<1	<1
	Ag	ppm	<1	<1	<1	<1	<1	<1	<1
	Na	ppm	<5	<5	<5	<5	<5	<5	<5
	Sn	ppm	<1	<1	1.4	0.4	0.4	0.6	<1
	Zn	ppm	0.4	<1	<1	<1	<1	0.2	0.2
	K	ppm	<5	<5	<5	<5	<5	<5	<5
	Sr	ppm	<1	<1	<1	<1	<1	<1	<1
	V	ppm	<1	<1	<1	<1	<1	<1	<1
	Ti	ppm	<1	<1	<1	<1	<1	<1	<1
	Cd	ppm	<1	<1	<1	<1	<1	<1	<1
D5188	V/L=20	degF	120.5	117.3	151.4	150.2	135.9	164.5	147.7
D525	RunTime	min	1440	1440	1440	1440	1440	1440	1440
	BreakY/N		NO BREAK	NO BREAK	NO BREAK	NO BREAK	BREAK	NO BREAK	NO BREAK
	BreakPt	min	N/A	N/A	N/A	N/A	123	N/A	N/A
	psiDrop	psi	89.1	43.8	77.5	63.9	105	25.1	20.6
D5453	Sulfur	ppm	36.4	30.5					
D5599	EtOHVol	Vol%	10.5301	19.5537	9.2052	8.9881	20.3994	19.774	16.5242
	EtOHWt	Wt%	11.3262	20.9893	9.5567	9.3118	21.4618	19.95	17.1372
	EtOHVol	Vol%	10.4041	19.5023	9.1381				
	EtOHWt	Wt%	11.1906	20.9341	9.487				
	EtOHVol	Vol%	10.3447	19.4049					
	EtOHWt	Wt%	11.1268	20.8296					
D6304	Water%	%	0.10506	0.23252	0.08343	0.07967	0.24539	0.25448	0.25005
	WaterPPM	ppm	1051	2325	834	797	2454	2545	2500
D7328	TChlorid	ppm	0	0	0	0	0	0	0
	TSulfate	ppm	0.4	0	0.2	0	0	0.5	0
	PSulfate	ppm	0.5	0.2	0.3	0	0.3	0	0.3