The Effects of Electronic Throttle Control Systems on Gasoline Internal Combustion Engine Compression Testing Procedures

1. ABSTRACT

Many new automotive vehicle designs incorporate an Electronic Throttle Control (ETC) system on the gasoline internal combustion engine to manipulate volumetric efficiency and control engine speed. These engines have the possibility of developing various mechanical problems at some point in the vehicle's lifespan. Compression testing is a common procedure used to diagnose certain types of engine mechanical problems. Compression testing procedures have traditionally been performed with a fully open throttle. However, ETC systems may not allow the throttle to open fully, if at all, during conventional engine compression test procedures. Technicians in the repair industry, students in vocational programs, as well as educators and trainers need to be aware of the effects of the ETC system on engine compression test procedures and make accommodations for these effects to reliably diagnose engine mechanical problems in these vehicles.

A sample of twenty-two vehicles equipped with an ETC system were gathered for testing. Compression testing procedures were performed on these vehicles to determine the throttle opening and cylinder pressures. The procedure was performed on each vehicle in three variations: (1) a conventional compression test, (2) Electronic Throttle Body (ETB) unplugged, and (3) ETB blocked open. The results of these testing procedures were analyzed to determine to what extent the throttle was opened by the ETC system during a traditional compression test. In addition, the variation in cylinder pressure among the tests was analyzed to determine if a statistically significant result existed. The results of the testing showed a wide variation in throttle openings among tested vehicles as well as a weak correlation between throttle opening and cylinder pressure. The conclusion of the study is that a conventional compression test is a valid testing procedure on ETC equipped vehicles.

2. INTRODUCTION

Within the past 25 years, automobile design has changed substantially. Integration of emerging technologies and software in vehicle design have led to dramatic improvements in fuel efficiency, emission reduction, and driver experiences (Dale, 2007, p. 41). One of these emerging technologies is the Electronic Throttle Control (ETC).

Spark ignition engines have traditionally, and for the most part continue to be, throttle governed. Throttle governing refers to the control of an engine's power output and/or speed through the manipulation of the amount of air allowed to enter the engine's intake manifold via a throttle body assembly. When the throttle is opened a small amount, only a small amount of air can enter the engine. This lowers the amount of power the engine can produce and minimizes the speed at which the engine can operate. When the throttle is opened further, more air enters the engine, increasing power output and engine speed. This manipulation of the throttle and airflow into the engine is affecting the engine's volumetric efficiency. By changing the engine's volumetric efficiency, the driver can increase or decrease the power output of the engine and ultimately the speed of the vehicle (Gilles, 2011, pp. 370-371) (Duffy, 2005, p. 21).

Before the advent of ETC, traditional vehicles were outfitted with a throttle cable or throttle linkage rod. These systems placed a mechanical link between the throttle body and the accelerator pedal. When the driver depressed the accelerator pedal, the throttle cable or linkage rod directly opened the throttle body and increased the engine's volumetric efficiency. This system was functional, but ETC systems have many benefits over the traditional mechanical linkage; improved vehicle drivability, throttle response, and fuel economy are expected from precise throttle manipulation. Integration of throttle control with adaptive cruise control, traction control, idle speed control, and vehicle stability control is now possible, leading to increased synergy between vehicle systems. Optimization of air supply will ensure harmful exhaust emissions are kept to a minimum. Reducing the number of moving parts requires less adjustment and maintenance (Pico Technology, 2015).

Also known by the term *drive-by-wire*, ETC uses Accelerator Pedal Position (APP) input signals from multiple sensors on the accelerator pedal to determine driver commands. When the driver depresses the accelerator pedal, these sensor signals change in relation to the amount of acceleration the driver desires. In a typical design, one APP signal will increase from low to high voltage as the accelerator pedal is depressed and another sensor signal will decrease, crossing paths at approximately half travel (Figure 1). Other designs use signals which both increase with APP movement, but at differing rates (Figure 2). These redundant sensor signals are used "to act as a plausibility test and also to ensure a degree of failsafe operation. (Pico Technology, 2016)." The APP sensor information is sent to a Powertrain Control Module (PCM). The PCM uses the APP signal inputs, as well as multiple additional powertrain sensor inputs, to make a decision about the proper positioning of the throttle. It is important to know that the PCM does not always open the throttle when the accelerator pedal is depressed. According to Dale (2007, p. 46), "When it's advisable, the output from the system can be a throttle angle command that's not what the driver requested. When there's a possible loss of traction and/or steering control, the ESC [Electronic Steering Control] system can overrule driver input to reduce throttle angle and engine power." Other examples of this phenomenon are stated to be normal vehicle operation by

Halderman (2015, pp. 277-278), “The engine may not increase above idle speed when depressing the accelerator pedal when the gear selector is in Park.” and “While at cruise speed, the accelerator pedal may or may not cause the engine speed to increase if the accelerator pedal is moved slightly.” The PCM will open the throttle by powering a bidirectional actuator motor inside the Electronic Throttle Body (ETB). When the ETB opens, atmospheric air is allowed to enter the intake manifold, increasing the volumetric efficiency of the engine and raising the engine speed (Hatch, 2009). In an electrically unplugged or disconnected condition, the ETB utilizes a concentric clock-spring to hold the throttle blade in a slightly open default position of approximately 16%-20%. The amount of air allowed to pass through in the default position will enable the vehicle to continue running in the event of a system failure, but not allow excessive engine RPM. The ETB bidirectional actuator motor is driven closed by the PCM to achieve engine speeds less than the default position would enable and driven open when higher engine speeds are desired (Halderman, 2015, p. 279). Multiple Throttle Position Sensors (TPS) are positioned on the ETB itself to verify that the desired throttle opening was obtained. Redundant sensor signals similar to the APP are used here for similar reasons. If the TPS signals indicate the commanded ETB position was not obtained, the PCM will set Diagnostic Trouble Codes (DTC’s) and can place the ETB into a performance limiting mode or forced idle mode as a safety precaution (McKay, Nichols, & Schreurs, 2000). ETC systems must be designed with safety redundancies and strategies to keep the driver safe in the event of a system failure.

Figure 1

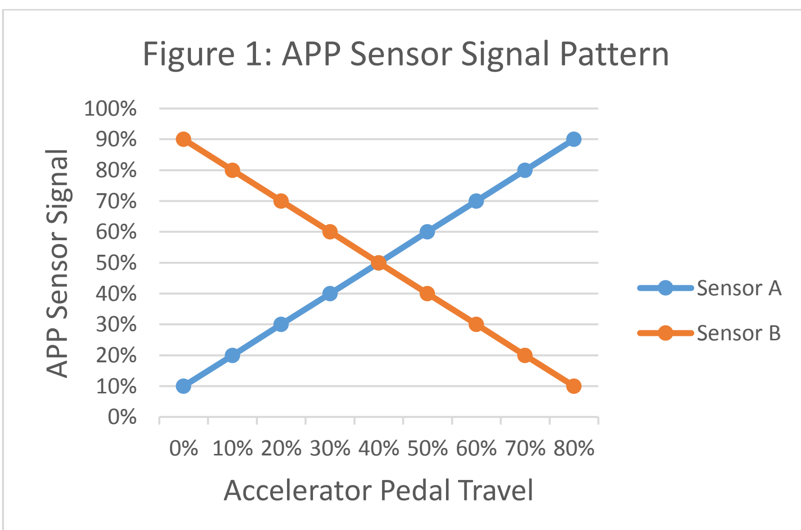

Figure 1: Example of a typical negatively correlated APP sensor signal pattern

Figure 2

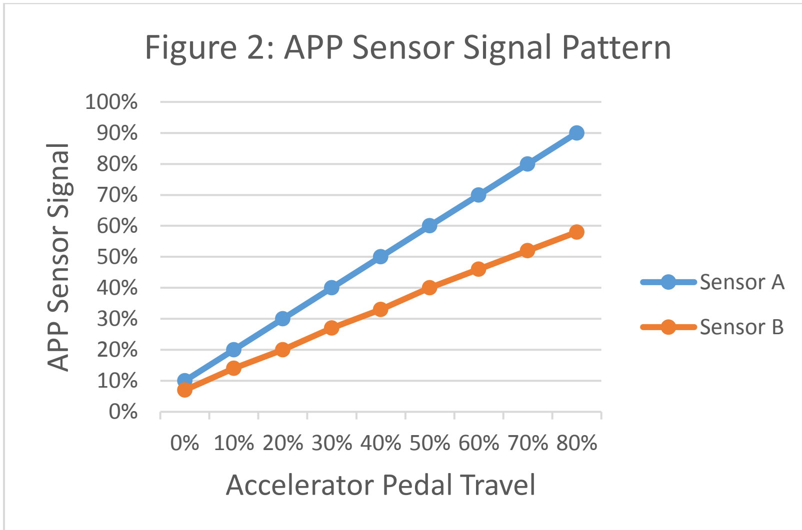

Figure 2: Example of a typical positively correlated APP sensor signal pattern

The compression test is a fundamental engine diagnostic test performed by automotive repair technicians and likewise taught in vocational education programs. Compression testing measures the air pressure created in the engine's cylinders during the compression stroke (Duffy, 2015, p. 387). The compression measurement is taken with a mechanical pressure gauge or electronic transducer which is connected to the engine cylinder's spark plug access port. A technician will use a compression test to assist in determining the root causes of various engine mechanical failures. A compression test can identify failures of the piston rings, cylinder head gaskets, exhaust valves, and many other potential mechanical issues (Halderman, 2008, p. 342). Other test procedures, such as a power balance test or cylinder leakage test can be used to identify engine mechanical failures. However, power balance testing is typically an initial test performed to determine if any weak cylinders exist, and cylinder leakage testing is performed to further diagnose a cylinder which has been identified to have low cylinder compression. In addition, issues causing intake or exhaust valves to not open properly, such as incorrect camshaft timing or worn cam lobes, are not able to be reliably diagnosed with a cylinder leakage test and usually require a compression test to properly identify the root cause (Greg's, 2012). Compression testers are a relatively inexpensive diagnostic tool and affordable for entry level technicians and students alike (Gilles, 2012, p 66). As such, a compression test is a valuable and cost effective method of diagnosing engine mechanical failures.

The procedure for performing a compression test can vary slightly between automotive manufacturers and training institutions, but many consistencies are noticed. Multiple compression test procedures were identified in various documents (Duffy, 2015, pp. 387-389; General Motors Corp., 2000; Gilles, 2011, pp. 66-68; Halderman, 2008; Krolic, 2014; Mitsubishi Motors Corp., 2002) and the following test steps were found in a typical compression test procedure:

- For best results, the engine should be warmed to normal operating temperature before testing.
- Disable the spark and fuel systems.
- All spark plugs of the engine should be removed to lessen the load on the starter motor.
- The battery should be fully charged.
- The throttle should be fully open.
- Install the compression test gauge into a spark plug bore.
- Crank the engine through at least 4 compression strokes.
- Record the pressure reading after the first cycle as well as the final pressure reading on the gauge.
- Continue to record the results for all cylinders.
- Look for cylinder pressure variations. Readings must be within 10%-30% of each other.

Although many consistent test steps were identified, a wide range of satisfactory cylinder pressure variations was also discovered. Though all test procedures recommended to identify consistent pressure readings among the tested cylinders, the spread of satisfactory test pressures ranged from 10% (Duffy, 2015), to 30% (General Motors Corp., 2000). Technicians and students performing a compression test on an engine would then be suspicious of test results with a pressure spread larger than 10% from the highest to lowest cylinders.

One test step in particular was found in almost every compression test procedure; Open the throttle fully. If the engine cannot take in any air, then no air would be available to compress. Opening the throttle fully eliminates any restriction to the volumetric efficiency of the engine. According to Halderman (2008), “Block open the throttle. This permits the maximum amount of air to be drawn into the engine. This step also ensures consistent compression test results.” In order to open the throttle fully a technician could physically block open the throttle plates from under the hood. This is not typical however. The usual manner of cranking the engine during a compression test is via the ignition switch. While sitting in the driver seat, cranking the engine, it is convenient for the technician to depress the accelerator pedal as the method of opening the throttle.

What happens when the vehicle requiring an engine compression test is equipped with ETC? We now know that an ETC system can control the throttle opening independently of the APP manipulation. Will the ETC system open the throttle fully from APP commands during a compression test? If the PCM does not command the ETB to open fully during the compression test, will the throttle opening affect the test and possibly result in an incorrect diagnosis? When the technician disables the spark and fuel systems, will the PCM identify a system fault and place the ETB into the default setting? Is having a fully open throttle really necessary when performing a compression test?

These questions will need to be answered to identify a valid procedure when performing a compression test on an ETC equipped vehicle. For the purposes of this research, the following questions have been chosen to test, specifically to ETC equipped vehicles:

Will the vehicle open the throttle fully when performing a conventional compression test procedure?

Will the amount of throttle opening affect the results of a compression test?

Is a unique compression testing procedure necessary?

3. METHODS

The research was performed at the SIUC Transportation Education Center using test vehicles from the Automotive Technology Department fleet. Vehicles were selected for the research based upon the presence of an ETC system, as well as being of a gasoline-fueled spark-ignition engine type. Diesel-fueled compression-ignition engines have higher cylinder pressures, require a specific compression tester, and were not considered to be included in the study. The sample group consisted of twenty-two vehicles which spanned across nine manufacturers, ranging from the model years 2004-2015 and engine displacement from 1.4L-5.7L. Engines from inline and V-type cylinder arrangements were represented. Vehicles were not required to run or communicate with the PCM to be considered for the study, however they were required to have a functioning engine starting system.

The compression tester used for the study was the Mityvac Digital Compression Test Kit (Lincoln Industrial Corporation MV5532). A digital gauge was desired for this study to provide an absolute number for the result and to eliminate any misinterpretation of an analog gauge reading. The test kit included the necessary adapters to connect the gauge to all of the sample vehicles. The tester gauge was adjusted to display cylinder pressure in the units of pounds per square inch (PSI) and displayed the unit to an accuracy of one decimal point. Lincoln Industrial

Corporation states the accuracy of the MV5532 compression tester is +/- 1% (personal communication, June 20, 2016).

The compression tests were performed by SIUC Automotive Technology students enrolled in the AUT-475 Special Projects course. The students chosen to perform the study were vetted by myself through an informal interview consisting of a discussion of prior experience, existing knowledge, and a performance evaluation. Only students who had previous training on engine compression testing were considered. Three students were selected who demonstrated the ability to perform the testing in a reliable and repeatable manner, as well as had the available schedule to participate.

To reduce systematic error an *ETC Vehicle Compression Test Worksheet* was developed which led the students to perform an identical test procedure for each sample vehicle. The worksheet was designed using compression testing procedures from existing textbooks and technical manuals. The worksheet included descriptive parameters for the test vehicles including make, model, and year of each vehicle. Students were asked to enter all vehicle information and to verify the presence of an ETC system on the vehicle. Each sample vehicle was brought through a testing readiness procedure which consisted of the installation of a scan tool, bringing the vehicle to normal operating temperature, verifying the battery voltage was at least 12.6 volts, and the installation of a low amperage battery charger.

At this point the ETC operation was verified with the ignition key in the run position. Any necessary air intake ducting was removed to expose the ETB and observe the movement of the throttle blade itself. The accelerator pedal was depressed fully, the movement of the ETB was observed, and the signals from the APP and TP sensors were recorded as a percent. If no TP signals were available through the scan tool, ETB opening was estimated.

3.1. Conventional Compression Test Procedure

The sample vehicles' fuel and spark systems were electrically disabled. This was accomplished by locating and removing the appropriate relays and fuses. In some cases, the ignition coils were also electrically disconnected to access the spark plugs. All accessible spark plugs were removed from the engine. Multiple sample vehicles would have required the intake manifold to be removed to access certain spark plugs. If the manifold had been removed, the volumetric efficiency of the engine would have been modified and invalidated the test results for this engine. In these cases, the manifold was not removed and only the cylinders which were readily accessible were tested. A compression test adapter was threaded into the spark plug port of the cylinder to be tested and the gauge attached to the adapter. The accelerator pedal was depressed fully and the engine was rotated through five compression strokes using the ignition switch. As the engine was being rotated by the starter, the APP and TP signals were observed from the scan tool and recorded. The cylinder pressure readings from the first and fifth compression strokes were recorded. Students performing the testing procedure would routinely employ video recording of the compression gauge to assist in gathering the cylinder pressure results. In cases when multiple students were available to perform the testing, this was unnecessary. This compression testing procedure was repeated on all available cylinders of the engine.

To determine whether the sample vehicle would open the throttle fully during a conventional compression test, the TP signals were analyzed. The mean, median, range, and standard deviation of these signals were calculated. Throttle position was analyzed among the parameters of manufacturer and model year to identify these as extraneous variables.

To determine whether the amount of throttle opening will affect the results of a compression test, the cylinder pressure readings obtained from this compression test were analyzed. Each vehicle tested had a measured pressure reading from each available cylinder of the engine. These cylinder pressure readings were averaged to obtain a *mean cylinder pressure* (MCP) of the engine. For each vehicle tested, the MCP for the conventional compression test was compared the MCP of the ETB blocked open compression test to measure the change in cylinder pressure.

3.2. ETB Unplugged Compression Test Procedure

The ETB assembly was electrically disconnected to place the throttle in the default position, and another compression testing procedure was performed on all available cylinders of the engine. During this test the TP signals were unavailable to monitor as the TP sensors are integral to the ETB assembly. Students were asked to estimate the percentage of TP opening at this time. The throttle position remained in the default position throughout this compression test. The MCP for each engine was determined from the results of this test and compared to the ETB Blocked Open Test to measure the change in cylinder pressure. Cylinder pressure data from 3 of the sample vehicles was thrown out due to errors in the testing process. However, throttle position data from all 22 vehicles was collected.

3.3. ETB Blocked Open Compression Test Procedure

A third compression test procedure was performed on the engine with a manually blocked open throttle plate. The ETB assembly was left unplugged and the accelerator pedal was not depressed; no signal data was gathered for TP or APP. The exposed ETB throttle blade was pushed fully open and physically blocked with an appropriately sized plastic screwdriver handle. This test was performed to replicate the function of a non-ETB vehicle with the accelerator pedal fully depressed and the throttle cable pulling the throttle fully open.

Cylinder pressure raw data for each vehicle was converted into an MCP. This test procedure was used as the baseline test for the other two test procedures. As a fully open throttle will maximize volumetric efficiency of the engine during the compression test, this test should theoretically also maximize the MCP of the engine. The MCP results of the baseline compression test for each engine were normalized at 100%. The MCP for the conventional and ETB unplugged compression tests were compared to the baseline MCP of the ETB blocked open test. A standard deviation of the MCP for each test was calculated to determine how close the compression test readings were from the three levels of throttle opening.

After the three compression testing procedures have been completed on all available cylinders of the engine, the vehicle was returned to a previous level of functionality, all DTC's were erased from the PCM, and the vehicle was returned to the fleet storage location. The process was repeated until all 22 vehicles completed the testing procedure.

4. RESULTS

4.1. Throttle Position Data

Before compression testing began the operation of the ETC system was verified on each vehicle. Of the 22 vehicle sample, 8 had no throttle reaction when the accelerator pedal was depressed fully and 14 did have some throttle reaction. Of the vehicles which had no reaction to accelerator pedal input, the TP signal indicated a range from 5.5%-19.2%. Of the vehicles which did react to the accelerator pedal input, the TP signal indicated a range from 21%-100%. Only one vehicle had no TP input available in the scan tool. This vehicle had no reaction to accelerator pedal input and the throttle angle was estimated to be approximately 15%. The APP signal for the sample was verified and the range was 71%-108%.

After the spark and fuel systems were electrically disabled, the operation of the ETC was again verified. The results of this observation were very similar to the initial verification with only two sample vehicles having different TP signals. One vehicle showed a reduction in TP input from 23.1% to 17.6% and another vehicle reduced TP signal from 100% to 36%.

4.1.1. ETB Blocked Open Compression Test Procedure

(Although the ETB blocked open test was the final compression test procedure performed on each sample vehicle, the results of this test will be given first as this test was used as the baseline for cylinder pressure comparisons.)

During this compression test the throttle body was electrically disconnected and the throttle blade was physically blocked open. No TP sensor input signals were generated during the test. Due to the throttle body being blocked fully open for this test, throttle opening was considered to be 100%.

4.1.2. Conventional Compression Test Procedure

During the conventional compression test the TP and APP signals were verified with a scan tool. The APP signals ranged the same as the initial verification, from 71%-108%. Of the sample, 6 vehicles had no throttle reaction during the test and 16 vehicles did have some throttle reaction. Of the vehicles which had no reaction to accelerator pedal input, the TP signal indicated a range from 7%-21%. Of the vehicles which did react to the accelerator pedal input, the TP signal indicated a range from 21.7%-100%. Five vehicles showed an increase in throttle opening between the initial verification process and the compression test, and one vehicle showed a reduction. Descriptive statistics of mean, median, range, and standard deviation for TP input data during this test are shown below in Table 4.1.1.

Table 4.1.1.

Mean	54
Median	53.5
Range	93
Standard Deviation	32.8

Table 4.1.1: Throttle Position (TP) % signal during conventional compression test procedure

Throttle opening during the conventional compression test was compared to the parameter of vehicle manufacturer using statistics of mean, median, range, and standard deviation. Of the vehicle manufacturers represented by two or more vehicles in the sample, the mean throttle opening ranged from 15.4% to 56.8%, the median ranged from 15.4% to 60.5%, the range varied from 0.7% to 82.4%, and the standard deviation ranged from 0.5% to 43.4%. Manufacturer specific TP input data is shown below in Table 4.1.2.

Table 4.1.2.

Manufacturer	# of vehicles in sample	Mean	Median	Range	Standard Deviation
GM	7	56.8	60.5	79	35.2
FCA	4	50.45	48.2	82.4	43.4
Ford	2	49.8	49.8	27.5	19.4
Nissan	2	54.8	54.8	54.5	38.5
Suzuki	2	15.4	15.4	0.7	0.5
Toyota	2	49.5	49.5	61	43.1
Honda	1	79	79	-	-
Mitsubishi	1	85	85	-	-
Volkswagen	1	86.7	86.7	-	-

Table 4.1.2: Throttle Position (TP) % signal during conventional compression test procedure (by manufacturer)

Throttle opening during the conventional compression test was also compared to the parameter of model year. Model year specific TP input data is shown below in Table 4.1.3.

Table 4.1.3

Model Year	# of vehicles in sample	Mean	Median	Range	Standard Deviation
2004	1	79	79	-	-
2006	4	37.2	57	84	41.3
2007	3	56.3	44.5	75	42.7
2008	2	45.5	45.5	36	25.5
2009	1	80	80	-	-
2010	1	86.2	86.2	-	-
2011	2	60.9	60.9	78.3	55.4
2012	2	20.1	20.1	1.8	1.3
2013	4	75.3	64.7	49.4	23.58
2014	1	36	36	-	-
2015	1	36	36	-	-

Table 4.1.3: Throttle Position (TP) % signal during conventional compression test procedure (by model year)

4.1.3. ETB Unplugged Compression Test Procedure

During this compression test the throttle body was electrically disconnected and the throttle body was allowed to rest in the default position. No TP sensor input signals were generated during the test. Throttle position was estimated by the student performing this compression test. The range of estimated throttle openings was 0%-79%. Removing the two outliers of 0% and 79%, the mean estimated throttle opening was 13% and the standard deviation was 6.5%.

4.2. Cylinder Pressure Data

4.2.1. ETB Blocked Open Compression Test Procedure

(Although the ETB blocked open test was the final compression test procedure performed on each sample vehicle, the results of this test will be given first as this test was used as the baseline for cylinder pressure comparisons.)

Pressure readings for all cylinders of each engine were averaged into a Mean Cylinder Pressure (MCP). A separate MCP was calculated for the first and fifth compression stroke of this compression test. Of the 22 vehicle sample, on the first compression stroke, MCP of the sample ranged from 71 psi to 152.5 psi. On the fifth compression stroke, MCP of the sample ranged from 139.8 psi to 250 psi. Cylinder pressure data for this test is shown below in Table 4.2.1.

Table 4.2.1.

	First compression stroke (PSI)	Fifth Compression Stroke (PSI)
Highest MCP	152.5	250
Lowest MCP	71	139.8
Mean	117	188.9
Median	115.3	185.5
Range	81.5	110.2
Standard Deviation	19.3	24.1

Table 4.2.1: Cylinder pressures obtained from ETB Blocked Open Compression Test (baseline)

4.2.2. Conventional Compression Test Procedure

Of the 22 vehicle sample, for the first compression stroke, the MCP of the sample ranged from 72.8-150 psi. These pressures equated to a result of 83.3%-114.68% of the MCP of the baseline test. Thirteen vehicles had an MCP less than the baseline test and 9 had a greater MCP. At the fifth compression stroke, the MCP of the sample ranged from 137.3-238 psi. These pressures equated to a result of 94.9% to 102.9% of the MCP of the baseline test. Fourteen vehicles had an MCP less than baseline test and 8 had a greater MCP. Cylinder pressure data for this test is shown below in Table 4.2.2. Cylinder pressure data compared to the baseline test is shown below in Table 4.2.3.

Table 4.2.2.

	First compression stroke (PSI)	Fifth Compression Stroke (PSI)
Highest MCP	150	238
Lowest MCP	72.8	137.3
Mean	114	186.7
Median	111.4	187.7
Range	77.2	110.7
Standard Deviation	19.7	23.9

Table 4.2.2: Cylinder pressures obtained from Conventional Compression Test

Table 4.2.3.

	First compression stroke	Fifth Compression Stroke
Highest MCP	114.68%	102.93%
Lowest MCP	83.3%	94.85%
Mean	97.68%	98.88%
Median	98.51%	98.94%
Range	31.38%	8.08%
Standard Deviation	8.3%	2.36%

Table 4.2.3: Mean Cylinder Pressure (MCP) of Conventional Compression Test compared to MCP of baseline test

4.2.3. ETB Unplugged Compression Test Procedure

Of the 19 vehicle sample, for the first compression stroke, the MCP of the sample ranged from 72-144.3 psi. These pressures equated to a result of 85.9%-113.9% of the MCP of the baseline test. Thirteen vehicles had an MCP less than the baseline test and 6 had a greater MCP. At the fifth compression stroke, the MCP of the sample ranged from 138.8-239.4 psi. These pressures equated to a result of 86.7% to 104.1% of the MCP of the baseline test. Thirteen vehicles had an MCP less than baseline test and 6 had a greater MCP. Cylinder pressure data for this test is shown below in Table 4.2.4. Cylinder pressure data compared to the baseline test is shown below in Table 4.2.5.

Table 4.2.4.

	First compression stroke (PSI)	Fifth Compression Stroke (PSI)
Highest MCP	144.3	239.4
Lowest MCP	72	138.8
Mean	110.9	186.9
Median	108.2	184
Range	72.3	100.6
Standard Deviation	18.7	25.8

Table 4.2.4: Cylinder pressures obtained from ETB Unplugged Compression Test

Table 4.2.5.

	First compression stroke	Fifth Compression Stroke
Highest MCP	113.9%	104.1%
Lowest MCP	85.9%	86.7%
Mean	97%	98.6%
Median	96.3%	98.9%
Range	28%	17.4%
Standard Deviation	6.3%	3.6%

Table 4.2.5: Mean Cylinder Pressure (MCP) of ETB Unplugged Compression Test compared to MCP of baseline test

5. DISCUSSION

As a result of this study, it has become apparent that vehicles equipped with ETC have unique characteristics which will affect throttle opening and cylinder pressure during a cranking compression test.

Looking at the throttle position signal data of the sample during the conventional compression test, we see a very spread out and inconsistent result (r = 93%, s = 32.8%). Comparing this data to model year and manufacturer showed no apparent correlation indicating these parameters as extraneous variables. The manufacturer group Suzuki and the model year group 2012 showed reasonably consistent throttle position (Suzuki r = .7, s = .5, 2012 r = 1.8, s = 1.3) though each group only had 2 vehicles. Having a larger sample with more consistent representation in each group might show a stronger correlation, although from the results of the study I would not infer this result. The throttle position data recovered from the conventional compression test can now be used to answer the first question posed earlier.

Will the vehicle open the throttle fully when performing a conventional compression test procedure? Not always. Though some vehicles did open the throttle fully during the test, due to the inconsistent results of the sample, a vehicle with ETC cannot be expected to open the throttle fully when performing a conventional compression test.

Now to look at the cylinder pressure data. Each engine was compared individually in MCP through the three unique compression testing procedures. The largest difference in measured MCP between the conventional compression test and the baseline test was found at the first compression stroke of the test (16.7%). The first compression stroke is recommended to be documented during a compression test as a method of determining piston ring health (Halderman, 2008), but in practice, I have not observed technicians routinely incorporating this test step. This particular engine had an identical cylinder pressure as the baseline at the fifth compression stroke (180 psi). In addition, this engine had a throttle opening of 86.2% during the conventional compression test. Comparing the fifth compression stroke of each engine tested showed a more consistent result among testing procedures. The mean MCP of the conventional compression test was 98.88% of the baseline. The mean MCP of the ETB unplugged compression test was 98.6% of the baseline. When comparing the range and standard deviation of the MCP of these two tests, the conventional compression test showed the greatest resemblance to the baseline (r = 8.08%, s = 2.36%) while the ETB unplugged test strayed further (r = 17.4%, s = 3.6%). Using this data, we can provide an answer to our second research question.

Will the amount of throttle opening affect the results of a compression test? The cylinder pressure data showed an unexpected series of results. The baseline test with the ETB blocked fully open was expected to provide the largest amount of cylinder pressure due to the maximized volumetric efficiency of the engine. While the average MCP of the two experimental tests were lower than the baseline, individually the vehicles of the sample were not consistently lower. Roughly a third of the sample showed a larger MCP on compression tests with less throttle opening. Therefore, the increase in cylinder pressure cannot be attributed to a larger throttle opening in this series of tests. While throttle opening may affect cylinder pressure, the results of this study did not show an absolutely positive correlation.

Finally we can answer the final research question: *Is a unique compression testing procedure necessary?*

The engine compression test is an invaluable method of diagnosing internal combustion engine mechanical problems. It is widely recognized and recommended by the automotive industry and currently taught in vocational schools and training centers. As a result of the integration of ETC technology, the effects of this system on the engine compression test must be known and accommodations must be applied to validate the diagnostic process. Consistent with the principles of this test is a reliance on consistency in cylinder pressures. Generally speaking, engine cylinders with compression further away from the average compression of the engine are deemed to perform more poorly than cylinders closer to the average. In order to have a reliable compression test with an accurate result the procedure should be as consistent as possible, allowing the test results to more closely describe the mechanical health of the engine. Looking at the two experimental test procedures, the conventional compression test resulted in a more consistent cylinder pressure result than the ETB unplugged test. In addition, the act of unplugging the ETB will cause the PCM will set DTC's and likely place the vehicle into a performance limiting mode and require additional procedures to clear this fault from the vehicle. From these results I will conclude the proper procedure for performing a compression test on a vehicle equipped with ETC should not include unplugging the ETB. Comparing the results of the baseline test to the conventional compression test, we see a slightly higher (1.2%) average cylinder pressure in the baseline, but an almost identical range and standard deviation. As the traditional compression test procedure considers cylinders with less than 15%-20% variation to be satisfactory, this result would not indicate the conventional compression test to be a great threat to a misdiagnosis. In fact, due to the possibility of damage to the ETB by forcing it open I cannot recommend blocking the ETB open when performing a compression test on a vehicle equipped with ETC. The variation between the conventional compression test and the baseline test was so small, in my opinion, I would recommend the conventional compression test as a valid and reliable procedure on ETC equipped vehicles.

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