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Performance and emissions of a methane fueled v-twin four stroke spark ignited engine

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Abstract: This paper discusses the on-going study of a modified two-cylinder V-twin engine used to research and analyze natural gas combustion. The purpose of the experimentation is to determine the feasibility of Natural Gas as an alternative fuel for automotive and stationary power generation applications. During testing the engine was operated under various loads and RPMs. The compression ratio (CR) of the engine was increased from 9.0:1 to 13.8:1 with the expectation of improved fuel combustion and improved emissions. The Exhaust Gas Recirculation (EGR) and air-fuel ratio (AFR) were also varied to determine optimal levels that would improve emissions without compromising excessive power (hp). Lean limit analysis was conducted to understand the effect of increased AFR on combustion and emissions. Results from testing confirmed an emissions benefit of going from low compression to high compression. The Total Hydrocarbons (THC) decreased 25%, Carbon Monoxide levels decrease by 48% and the Oxides of Nitrogen (NOx) decreased by 20%. A low percentage of EGR, between 3-6 %, helped reduce Oxides of Nitrogen (NO_x) emissions from over 830 ppm to less than 450 ppm, an improvement of almost 50%, with less than a 2% increase in THC and CO. Power (hp) actually improved by about 1.5% with 3% EGR. Increasing the AFR proved to decrease emissions but at a cost of power and the lean limit of the engine was found to be between 22 and 23 AFR. At 22 AFR the THC emissions decreased by 40%, CO emission by 90% and NOx emissions by almost 50%, but the power decreased by over 35%.

Keywords: Compressed Natural Gas, Combustion, Emissions, Exhaust Gas Recirculation, Air Fuel Ratio, Compression Ratio

1. Introduction

Rising oil prices and a global emphasis on the reduction of pollution has prompted the search for an alternative fuel sources [1-6]. The development of Compressed Natural Gas (CNG) engines is a solution to help alleviate dependence on oil and reduce emissions caused by the transportation sector. Natural gas is one of the most promising alternative fuels and is cheaper and cleaner burning than its gasoline and diesel equivalents [7-9]. Natural gas is also readily available throughout the world [10] with reserves in the U.S. increasing every year since 1999 according to the U.S. Energy Information Administration (EIA) [11].

Although natural gas has a lower energy density than gasoline or diesel, research has shown that a natural gas engine has the potential for increased efficiency and lower emissions [12]. Natural gas has a very high Research Octane Number (RON) of 130, allowing the engine to be run at higher compression ratios without knocking [13]. Another benefit of natural gas fuel is the lower emissions which is reduced even further through the use of lean burn operating techniques [9].

Lean burn, defined as an Air Fuel Ratio (AFR) that is greater than what is stoichiometric for a given fuel (17.2:1 for CNG), also has the advantage of increased thermal efficiency due to an increased ratio of specific heat [14]. Air has a higher ratio of specific heat compared to natural gas (methane) so as more air is added and the mixture of air and fuel becomes leaner, the AFR the ratio of specific heats also increases.

$$\gamma \text{ (Ratio of Specific Heats)} = Cp/Cv \tag{1}$$

$$\gamma_{air} = 1.40 \tag{2}$$

$$\gamma \text{ Natural Gas (Methane)} = 1.32 \quad (3)$$

CNG is not only a viable alternative fuel for Spark Ignition (SI) applications, but it also has the potential to match the high power density of other fuels with the development of Homogenous Charge Compression Ignition (HCCI) [10, 12, 15, 16]. HCCI holds great potential for increasing the energy density and efficiency of natural gas engines. But HCCI engines have been very problematic when implemented for transportation applications. It is very difficult to achieve precise control over the combustion process and maintain the engines efficiency over a wide range of operating conditions with HCCI [12]. For these reasons many of the current developments in HCCI engines have focused on stationary power generation [12, 17].

In this investigation we will be focusing on Spark Ignition (SI) natural gas engines and the feasibility of compressed natural gas as an alternative fuel source for mobile as well as stationary applications. Acquisition and analysis of the engine data will increase understanding of the benefits of CNG as well as provide insight into the combustion phenomenon. Various dynamics of engine performance including Compression Ratio (CR), AFR, Exhaust Gas Recirculation (EGR), RPM and Engine Load will be explored.

1.1. Goals

- Operate, analyze and document the operation of the Natural Gas Engine.
- Optimize the engine performance and determine the effects of seven engine parameters including location of peak in-cylinder pressure (PPL), indicated mean effective pressure (IMEP), air fuel ratio (AFR), engine RPM, engine load, and Exhaust Gas Recirculation (EGR).

1.2. Objectives

- Reduce engine emissions (CO, THC, NO_x)
- Understand the factors that drive CNG fueled engine performance and emissions.
- Investigate Lean Limit operation.

2. Experimental Apparatus

Figure 1. *Kohler Command Pro ECH-749 and Test Stand*

A modified Kohler Command Pro ECH-749 two-cylinder V-Twin engine with Electronic Fuel Injection (EFI) was used to investigate the capabilities and feasibility of a natural gas engine. The engine was converted from gasoline to CNG. Existing fuel injectors were replaced with prototype Delphi CNG injectors. Higher heat range spark plugs, RC14YC (2 heat ranges higher than stock), were installed and the production Engine Control Unit (ECU) was replaced with a programmable development ECU which could be modified to account for the unique properties of methane fuel. A Delphi linear EGR system was also installed. Table 1 shows detailed specifications of the engine.

Table 1. *Engine Specifications*

Base Engine	Kohler Command Pro ECH-749 EFI
Type	2-Cylinder V-Twin
Cycle	4-Cycle
Compression Ratio	13.8:1
Displacement	747 CC
Bore/Stroke	3.27/2.72 in
Oil	5W-30 Synthetic
EGR Valve	Delphi Linear EGR-1

The engine was installed in a GDJ Powertek® Engine test stand consisting of a 30 hp eddy current dynamometer directly coupled to the engine as seen in Figure 1. The dynamometer provides a variable load to the engine that can be manually adjusted via an operator control box. Adjacent to the control box is an engine throttle that is cable driven with a Vernier control. A load cell connected to the dynamometer measures torque (ft-lbs); power can be calculated based on the torque reading and engine speed.

Various modifications were made to the engine test stand including an upgraded Digital-to-Analog Converter (DAC) along with upgraded control and test sensors used for data collection. Kohler's Command Pro EFI engine management system and original engine sensors were used. Combustion data was logged and analyzed with Nation Instruments LabView software along with TFX Engine Technology data loggers and software. A list of test equipment and sensors are listed in Table 2.

Table 2. *Supplemental Test Equipment and Sensors*

Mass Air Flow	Sierra series 620S Fast-Flo Insertion Flow Meter
Mass Fuel Flow	Sierra Smart-Trak 2 Series 100 Flow Meter
TFX Data Logger	DBS Basic 5
TFX Sensor Interface Box	SB4/5
Combustion Pressure Sensor	Optrand AutoPSI Pressure Sensor
Incremental Rotary Encoder	BEI Model H25 Incremental Encoder
O2 Sensor	AEM UEGO Controller & Bosch LSU 4.2 Sensor
Temperature Sensors	K-Type Thermocouples

Emission testing was conducted with the assistance of Delphi® Inc. using their equipment at their state-of-the-art facility in Rochester, NY. A Horbia Emissions system was used to capture emission data for NOx, CO, CO_2 and THC. All exhaust emissions were measure using the ISO-certified equipment listed in Table 3.

Table 3. *Delphi Emissions Equipment*

NOx	Chemiluminescents – Horiba CLA-22A
CO	Non-Dispersive Infrared Detector – Horiba AIA-23
THC	Flame Ionization – Horiba FIA-23A
CO2	Non-Dispersive Infrared Detector – Horiba AIA-23

After initial testing was completed the compression ratio was increased from 9.1:1 to 13.8:1. High compression pistons (no dome – flat top) were installed, see Figure 2. The production heads were also replaced with high strength steel heads.

Figure 2. *Low Compression vs. High Compression Pistons.*

3. Initial Experimentation

Initial Testing of the engine was conducted at low compression (9.1:1) for a baseline comparison test of gasoline versus CNG fuel. During testing the engine was operated under various engine loads, RPMs, and Exhaust Gas Recirculation (EGR) percentages. The range of parameters tested are listed in Table 4.

Table 4. *Low Compression Testing Parameters.*

RPM	2400, 3200
Load (%)	25, 50, 75, 100
EGR (%)	1, 6, 9, 12, 15, 18

Emissions results in Figure 3 show a comparison of gasoline vs. CNG. The engine was operated at 3200 RPM and maximum load. Emissions, Power, Torque and maximum in-cylinder pressure were recorded. There was approximately a 70% decrease in NOx emissions while THC and CO both increased. The engine was not calibrated for CNG fuel during this test so poor fuel combustion may have caused the increase in THC and CO emissions.

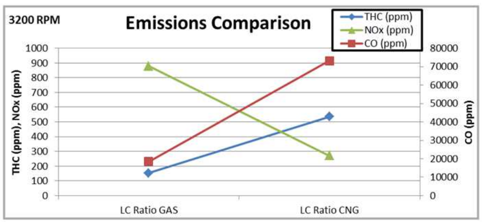

Figure 3*. Emissions Comparison of Low Compression Ratio Gasoline and Low Compression Ratio CNG.*

Combustion results in Figure 4 show a slight decreases in power (hp) and torque (ft. lbs.), about 1% and 2% respectively for CNG compared to gasoline. The results also show an increase in maximum cylinder pressure from 339 to 343 PSI for CNG as compared to gasoline.

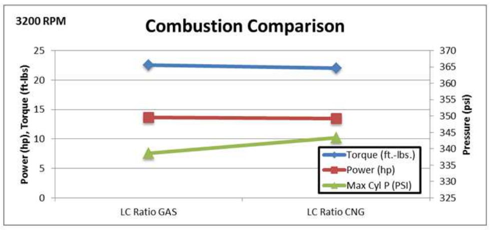

Figure 4*. Combustion comparison of Low Compression Ratio Gasoline and Low Compression Ratio CNG.*

4. High Compression Experimentation

High compression experimentation (CR=13.8:1) was conducted using CNG fuel. During testing the engine was operated under various loads, RPMs, EGR percent, and AFR's. In addition, a lean limit analysis was conducted to understand the effects of increased AFR on combustion and emissions.

Table 5. *High Compression Testing Parameters.*

RPM	2400, 3000, 3200, 3600
Load (%)	25, 50, 75, 100
EGR (%)	1, 3, 6, 9, 12, 15
AFR	15, 16, 17, 19, 22

Figure 5 shows an emissions comparison of low compression CNG (CR=9.1:1) to high compression CNG (CR=13.8:1). Results show over a 20% decrease in THC, about a 48% decrease in CO and about a 20% decrease NOx emissions.

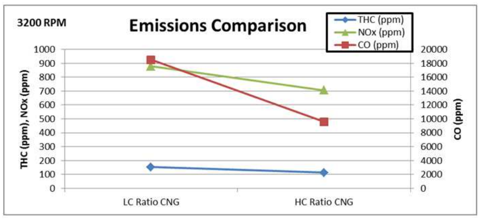

Figure 5. *Emissions Comparison of Low Compression Ratio CNG and High Compression Ratio CNG.*

Figure 6 shows a performance comparison between low compression ratio CNG to high compression ratio CNG. Results show and increase in power (hp) of 7%, and increase in torque (ft-lbs.) of 8% and an increase in the maximum cylinder pressure of 8%.

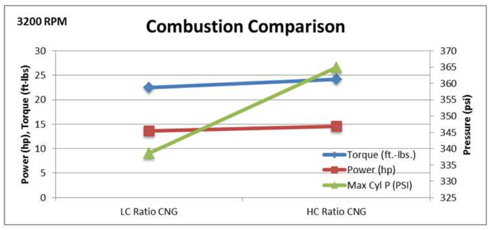

Figure 6. *Combustion Comparison of Low Compression Ratio CNG and High Compression Ratio CNG.*

5. Exhaust Gas Recirculation

To test the effect of EGR on emissions and combustion the EGR was varied from 0% to 15%. The equation used to calculate EGR percentage is listed as Equation 4.

$$\text{Total EGR} = (m_{recycle}/m_{cyl\ tot})*100 \quad (4)$$

The amount of EGR is controlled with Delphi Linear EGR-1 Valve. The EGR percentage is based on the mass of exhaust gases recirculated back into the engine. The mass of exhaust gas exiting the engine was measured using the real time measurements produced by the Delphi emissions testing equipment. The Delphi test facility EGR calculation is based on a general combustion equation listed as Equation 5. [18]:

$$CH_YO_Z+n(O_2+\varepsilon N_2)+$$

$$\frac{EGR}{100}\left(aCO_2+bH_2O+cC_3H_{3y}+dNO+eH_2+fO_2+gCO+hN_2\right)$$

$$\rightarrow aCO_2+bH_2O+cC_3H_{3y}+dNO+eH_2+fO_2+gCO+hN_2 \quad (5)$$

The testing was conducted varying engine load and RPM (see Table 5). Figure 7 shows that when a small percentage of EGR is added, up to 3%, there is a significant drop in NOx emissions and only a slight increase in THC and CO levels. As more EGR was added THC and CO levels start to rise considerably, while NOx levels continue to drop. When the EGR percentage reached over 12% the engine performance became erratic.

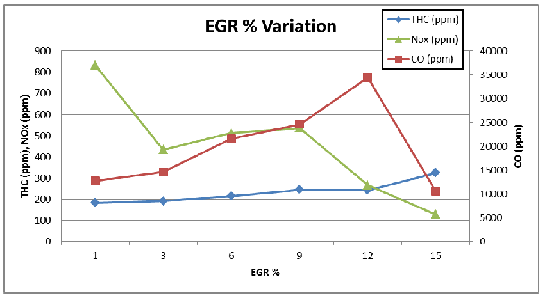

Figure 7. *Effect of EGR on Emissions.*

Figure 8 shows the effect of EGR on power. Similar to the emissions results, a small percentage of EGR proved to be beneficial, but as more EGR was added the power began to decrease significantly.

6. Air Fuel Ratio

Figure 9 shows emissions as a function of the air/fuel ratio. This testing was conducted for the loads and RPMs listed in Table 5. THC levels gradually decreased until reaching a AFR of 19 and then began to increase. CO levels decreased as AFR increased and NOx levels although increasing initially began to drop after reaching an AFR of 17. Further testing of the effect of AFR on emissions was conducted during the lean limit testing and the results are given in Section 7.

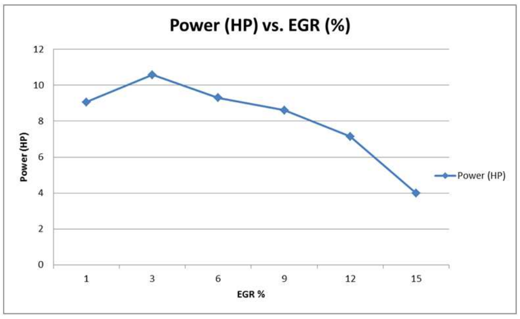

Figure 8. *Effect of EGR on Power.*

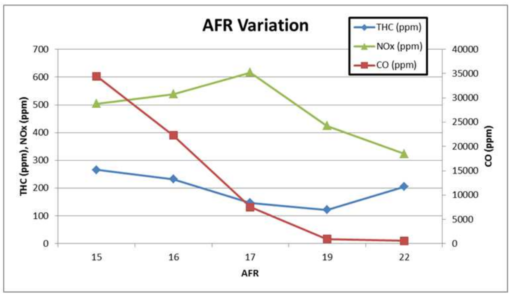

Figure 9. *Effect of AFR on Emissions.*

Figure 10 shows the effect of AFR on Power. As AFR was increased and the engine was running leaner the power began to drop until an AFR of 22 where the power was approximately 50% of the maximum.

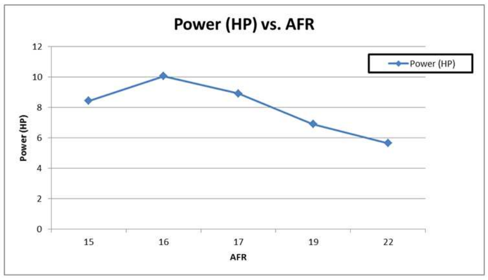

Figure 10. *Effect of AFR on Power (hp).*

Figure 11 shows the maximum cylinder pressure of both cylinders 1 and 2 as the AFR was increased. Figure 12 shows the IMEP for both cylinders as AFR was increased. Both the maximum cylinder pressure and IMEP decreased as the AFR increased beyond 16.

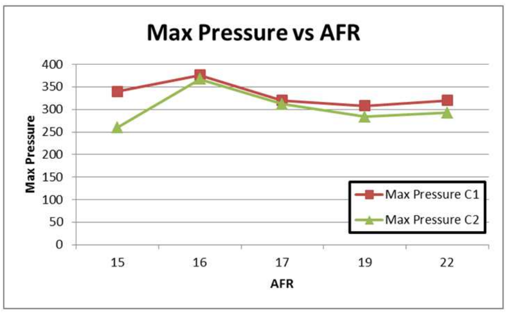

***Figure 11**:* Maximum Cylinder Pressure (PSI) versus AFR.

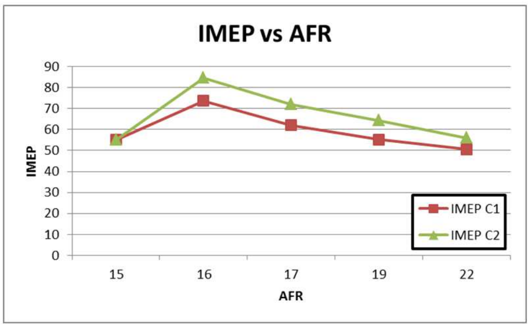

__Figure 12.__ Indicated Mean Effective Pressure versus AFR.

7. Lean Limit Testing

The lean limit is defined as the maximum air-fuel ratio where the engine may run without misfiring [19]. Lean limit testing was conducted at the load and RPM points listed in Table 5. The engine ran at the leanest calibration possible at each point and the fuel pressure regulator was used to vary and control the AFR. Running the engine near the lean limit has the potential to significantly reduce emissions, especially that of NOx.

Figure 13 shows the effect of AFR on emissions as the AFR was increased and approached the lean limit. The lean limit was determined to be between 22 and 23 AFR after which the engines performance becomes erratic and unstable. Up to an ARF of 23% there was a significant improvement in emissions. Results show an exponential decrease in NOx as the engine ran leaner. THC and CO levels also show improvement until reaching the lean limit, after which they begin to increase significantly.

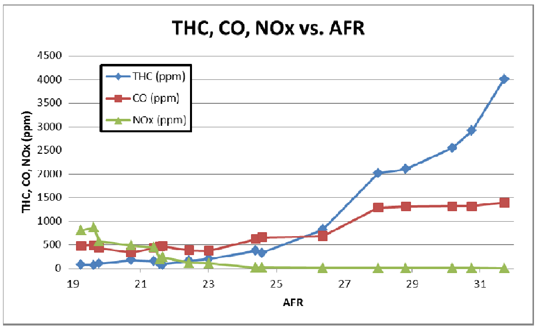

__Figure 13.__ Lean Limit Emissions Results.

Although running lean can greatly benefit emission it does come at a cost. Both Power (hp) and IMEP decreased linearly as show in figures 14 and 15, respectively.

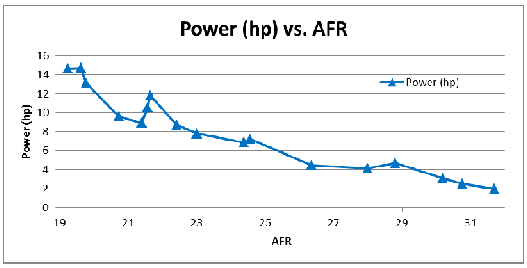

__Figure 14.__ Lean Limit Power Results

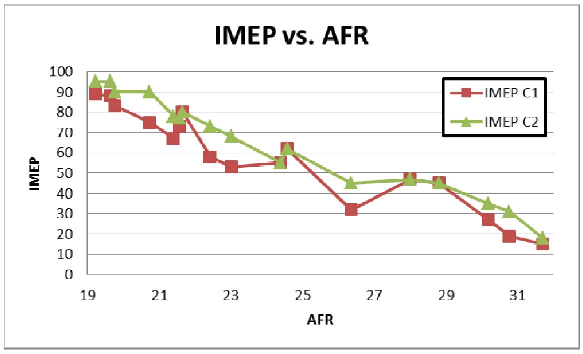

__Figure 15.__ Lean Limit IMEP Results.

Figure 16 shows the IMEP at various AFR levels for both cylinders, cylinder 1 in blue and cylinder 2 in yellow. As the AFR was increased the IMEP began to drop significantly. The data also shows that when the AFR is increased above the lean limit the IMEP became more erratic and there were significant pressure fluctuation between cycles.

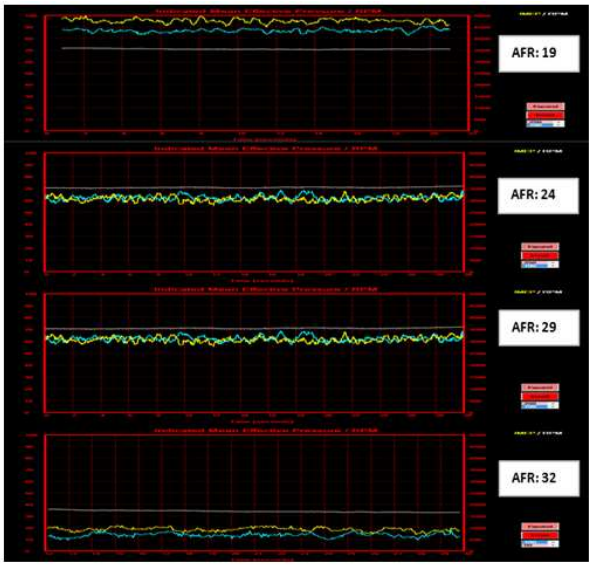

__Figure 16.__ IMEP vs. AFR

8. Conclusions

A modified two-cylinder V-twin engine was used to analyze natural gas combustion and the resulting emissions. The CR of the engine was increased from 9.0:1 to 13.8:1 improving the engines performance. During testing the engine was operated under various loads and RPMs. In addition, the Exhaust Gas Recirculation (EGR) percent and the air-fuel ratio (AFR) were also varied. The following conclusions were drawn from this investigation:

- CNG combustion emissions were improved as the compression ratio increased from 9.0:1 to 13.8:1. The THC decreased by 25%, CO levels decrease by 48% and the NOx decreased by up to 20%.
- There was a decrease in power produced by the engine when it was fueled with natural gas as compared to gasoline. The baseline test at 3000 RPM, maximum

load, produced 8% less power with CNG as compared to gasoline.

- A low percentage of EGR, between 3-6 %, reduce NO_x emissions from over 830 ppm to less than 450 ppm, with only a 2% increase in THC and CO. Power (hp) improved by approximately 1.5% with 3% EGR, but began to decrease as more EGR was added.
- Running the engine lean proved to substantially improve emissions, but at a cost of power (hp).
- The lean limit of the engine was found to be between 22 and 23 AFR. NOx emissions exponentially decreased as the engine was run leaner. When the lean limit was exceed THC and CO levels began to increase significantly.

9. Future Plans

This project is an ongoing investigation of Compressed Natural Gas engines. The investigation has shown great potential in CNG as an alternative fuel to gasoline and diesel fuel and further testing will be conducted.

9.1. Lean Burn Operation

The lean limit testing has shown great potential for improving emission and efficiency, further lean limit analysis will be important to better understand the effects of lean burn.

9.2. Increasing the Compression Ratio

Higher compression ratio has potential to increase efficiency, improve combustion, and reduce emissions.

9.3. Spark Advance

The current ignition timing is not optimal. There is room to improve combustion by advancing the ignition timing. This will help maximize the cylinder pressures and has the potential to improve emissions as well as engine efficiency.

9.4. HCCI

Homogenous charge compression ignition has great potential for better emissions and improved engine performance. With an increased compression ratio it may be feasible to reach HCCI with this engine.

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Nomenclature

AFR	Air/Fuel Ratio
CA	Crank Angle
CAD	Crank Angle Degree
CH4	Methane
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO2	Carbon Dioxide
CR	Compression Ratio
EFI	Electronic Fuel Injection
EGR	Exhaust Gas Recirculation
IMEP	Indicated Mean Effective Pressure
K	Kelvin
NO	Nitric Oxide
NOx	Oxides of Nitrogen
O2	Oxygen
PHEV	Plug-in Hybrid Electric Vehicles
PPL	Location of Peak In-Cylinder Pressure
SOC	Start of Combustion
TDC	Top Dead Center
THC	Total Hydrocarbons
ppm	parts per million
γ	Ratio of Specific Heats

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