

Effect of Syngas (H_2/CO) on SI Engine Knock under Boosted EGR and Lean Conditions

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ABSTRACT

Syngas (synthesis gas) aided combustion from various fuel reforming strategies is of increasing interest in boosted lean burn SI engines due to its impact on dilution tolerance and knock resistance. Due to the interest in reformed fuels, more concrete understanding of how to leverage syngas supplementation under various lean conditions is essential to optimize engine performance and derive the most benefit from the availability of syngas in the combustion process. While the impact of syngas supplementation on combustion stability has been studied adequately, detailed understanding of the impact of syngas on knocking is still limited. Hence, this study investigates the effect of syngas (H_2/CO) addition on knock tendency under boosted EGR (Exhaust Gas Recirculation) and air diluted conditions. Syngas amount is controlled on an energy basis from 0% to 15% to compare the difference between EGR and air dilution. At first, several knock quantification methods are compared, and a suitable knock index and guideline are selected. Knocking tendencies with respect to the frequency, combustion phasing, and burn duration are analyzed based on observed engine knock. Also, the thermal efficiency and emissions difference are discussed as well. The results show that with increasing the syngas supplementation ratio, knocking is strongly suppressed, and the effect is more beneficial with EGR dilution than with air dilution.

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1. INTRODUCTION

Boosted EGR (Exhaust Gas Recirculation) or air diluted lean burn SI (Spark Ignition) engines offer considerable thermal efficiency benefits compared to naturally aspirated SI engines [1, 2, 3]. By increasing boost level, thermal efficiency increases due to the rise in volumetric efficiency and reductions in pumping and friction losses. Additionally, with higher dilution levels, efficiency is improved as a result of lowered peak cylinder temperature and increased specific heat ratio (γ) of the working fluid [4]. However, with increasing boost level and dilution ratio, combustion instability and engine knock are severely increased due to mixture and cylinder conditions.

To counteract the stability and knocking problems of SI combustion under boosted lean conditions, synthesis gas, which is generally comprised of hydrogen and carbon monoxide, supplemented combustion is one of the most promising methods in the advanced combustion field due to its impact on dilution tolerance and knock resistance [5, 6, 7]. Hydrogen has faster flame speed as well as higher octane number, so it helps to improve combustion stability and knock mitigation. Carbon monoxide also has relatively high octane number, so it helps to reduce knocking tendency as well. In addition, it is known that when carbon monoxide oxidizes in the presence of water vapor, such as with EGR or water injection, the knocking tendency is decreased due to inhibition of auto-ignition because $CO + OH \rightarrow CO_2 + H$ reaction [8].

The most practical way to supply syngas to an engine is through fuel reformation. As a consequence, a variety of on-board fuel reforming systems have been developed such as in-cylinder reformation [9,10], plasmatron [11], solid oxide fuel cell [12], endothermic catalytic reformer using exhaust waste heat [13,14], etc. However, the reforming capacities and product compositions of these systems are diverse, so adequate guidelines and concrete understanding of how to leverage syngas addition are essential to optimize engine performance based on the flammability and knock limits of lean boosted condition.

Up to the present, many studies have considered the effect of hydrogen or syngas addition on combustion stability in boosted lean burn SI engines [15, 16, 17]. Studies on the effect of syngas on engine knock, however, are still limited, and the relation between the addition of syngas and knock mitigation varies depending on operating conditions. Shinagawa et al.[18] demonstrated that hydrogen addition decreases engine knocking tendency due to reduced burn duration and inhibition of fuel decomposition and radical production under rich conditions. Gerty et al.[19] conducted a reformat fuel addition experiment under stoichiometric conditions, and results showed that 30% reformat addition decreases the required octane number by more than 10, and the change in required octane number is affected by fuel composition. Topinka et al.[7] described that 15% of fuel reformation increases by 10 the octane number of a fuel mixture under air diluted lean conditions mainly due to slowing the ignition of the end-gas. However, with increasing air-fuel ratio at constant fuel mass and intake air boosting, knock

tendency increases as a result of peak pressure and temperature rise. In contrast, Chen et al.[20] asserted that knocking is increased with hydrogen addition under lean conditions. Therefore, a clear explanation of knock and lean combustion is essential.

The focus of this study is to examine and compare the knock trends between boosted EGR and air diluted lean conditions with varied syngas addition amount. First, multiple knock indices are applied, and the propensity of knock under EGR and lean conditions is discussed. In addition, combustion and knock are examined with respect to the combustion phasing, burn duration, efficiency, and emissions.

2. EXPERIMENTAL SETUP

Engine and Fuel Specifications

All experimental data presented in this study were obtained with a boosted Ricardo Hydra single cylinder research engine at the W.E. Lay Automotive Laboratory at the University of Michigan. Two fuel injection systems were used in this experiment; one is port fuel injection for gasoline and the other one is a gaseous fuel fumigation system for syngas supplementation. Both fuel systems have fuel flow meters to enable calculation of the air-fuel ratio independently from the exhaust lambda meter and the emission bench air-fuel ratio calculation.

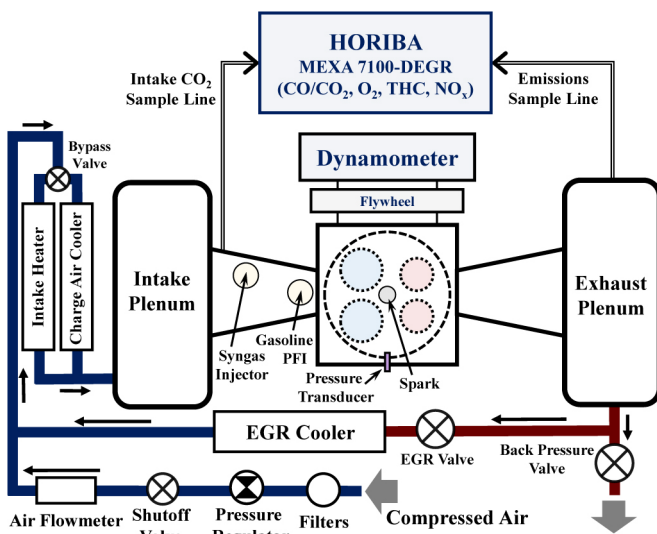


Figure 1. Schematic of Boosted Ricardo Hydra Single Cylinder Research Engine.

Table 1. Boosted Hydra Single Cylinder Research Engine specifications and operating conditions.

Displaced volume	0.5 L
Bore / Stroke	86 mm / 86 mm
Compression Ratio	10.5 : 1
Intake Valve Timing	IVO: 362 bTDCign / IVC: 136 bTDCign
Exhaust Valve Timing	EVO: 138 aTDCign / EVC: 364 aTDCign
Head Design	Pent-roof / 4 Valve / Central Spark
Engine Speed	1500 rpm
Intake Air Temperature	26.5 °C ± 0.75 °C
Coolant Temperature	85 °C
Oil Temperature	85 °C

The engine includes an external cooled EGR loop controlled by back pressure and EGR valves. The intake air temperature is regulated with a by-pass heater and a cooler located in front of the intake plenum. The schematic in figure 1 shows the air flow path and major components of this engine. The engine has a compression ratio of 10.5:1 and the cylinder pressure transducer (Kistler 6125A piezoelectric transducer) is 4mm in diameter and is located on the side of the head. The transducer is used for the in-cylinder pressure measurement, and the signal is amplified (AVL IFEM) and recorded (AVL Indiset module) with a crank angle encoder signal (AVL 365C01).

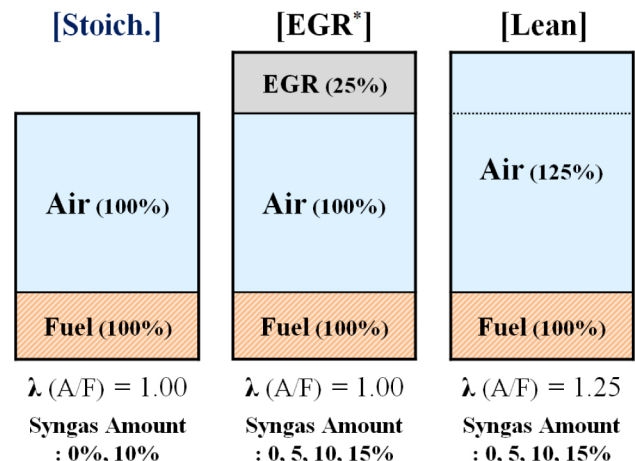
The gasoline fuel used in this study is HF0072 research grade gasoline provided by Haltermann Solutions Ltd. The research octane number is 91.1 and motor octane number is 83.0 (sensitivity of 8.1). Syngas composition is 43.97 mole% of hydrogen and 56.03 mole% of carbon monoxide using bottled gas provided by Airgas. The composition of syngas is motivated by the plasmatron reformat fraction [7].

Table 2. Fuel (Gasoline, Syngas) Specifications.

	Gasoline (HF0072)	Syngas [7,21]	
		H ₂ (44%mol)	CO (56%mol)
Research Octane Number	91.1	> 130	106
Lower Heating Value [MJ/kg]	43.1287	120	10.1
Stoichiometric A/F ratio	14.52	34.2	2.47
Hydrogen / Carbon ratio (mole basis)	1.8805	-	-
Oxygen / Carbon ratio (mole basis)	0.0	-	1.0

Experimental Condition

To explore the effects of the synthesis gas supplementation on knocking under different dilution conditions, both stoichiometric and EGR / Air diluted experimental conditions were considered. Prior to the comparison experiments at diluted conditions, stoichiometric experiments were performed with gasoline only and with syngas supplement on a 10% energy basis to find MBT (Maximum Brake Torque) and knock limited points. The intake pressure was varied from 0.4 to 1.6 bar with 0.1 bar intervals and spark sweep was done in each intake pressure case. The engine speed for all experiments is controlled to 1500rpm.



$$* \text{ EGR mass fraction} = 20\% \left(= \frac{25\%}{100\% + 25\%} \times 100 \right)$$

Figure 2. Air Fuel ratio and experimental conditions. (Stoichiometry, EGR, and Lean conditions)

For the comparison experiments between EGR and lean conditions, the intake and exhaust pressures are fixed to 1.20 and 1.40 bar respectively, and a schematic of EGR and air diluted conditions is shown in figure 2. Based on the stoichiometric air mass, additional 25% of EGR and air is added in cylinder. Thus, the EGR mass fraction of the charge is controlled to 20% with lambda value of 1.00, and the lambda value of the lean condition is 1.25. The intake and exhaust pressures are kept constant in all comparison tests to avoid the possibilities of internal EGR effects. The fuel energy is kept constant in all identical intake pressure conditions, and the syngas amount is controlled on an energy basis from 0% to 15% in 5% intervals.

Since the knock behavior is very sensitive to day-to-day changes in ambient conditions, each comparison experiment is performed on the same day, and identical sets are repeated for a total of three times on different days to test repeatability.

Air Fuel Ratio and EGR Measurement

To measure and control the air fuel ratio in real time, both the ETAS LA4 lambda meter and the Horiba MEXA 7100-DEGR emissions bench are used. Lambda meter has a faster response than the emissions bench, so all data recording is done after stabilization and matching of these two air-fuel ratio values. In addition, recorded fuel and air flow based calculations are analyzed as a post processing step to check the air-fuel ratio values again.

$$EGR_{ratio} [\%] = \frac{CO_2 (intake) - CO_2 (ambient)}{CO_2 (exhaust) - CO_2 (ambient)} \times 100 \quad (1)$$

EGR ratio is controlled based on the emissions bench measured value using equation 1.

3. KNOCK QUANTIFICATION

There are several techniques to characterize engine knock such as cylinder pressure trace, audible knock, engine block vibration measurement, and intermediate radical species detection, and each method has specific objectives. Because the focus of this study is in-cylinder physical knock, the cylinder pressure and audible knock measuring methods are used to detect and quantify the engine knock.

Filtering Cylinder Pressure

In order to obtain knock measurements from the raw in-cylinder pressure trace, an appropriate filtering process is essential. The most commonly used pressure-rectifying method, Fast Fourier Transformation (FFT), is used in this study. The process of FFT based filtering involves converting raw pressure signals from the time to the frequency domain, and applying a high pass filter with a certain cut-off frequency, and then inverting the data from the frequency to the time domain.

Figure 3 shows the converted frequency domain cylinder pressure data from motoring to heavy knock for the baseline condition. Normally, lower frequencies represent the signal associated with compression and the standard flame propagation heat release, so a

high pass filter is generally used to filter the knocking data. The cutoff frequency of the high pass filter is selected by comparing the knocking and non-knocking frequency domains. As the amplitudes of motoring, normal, and light knock signals illustrate in figure 3, most of the normal combustion frequency is located under 3 to 4 kHz. So, the cut-off frequency of this study is chosen to be 3500 Hz as illustrated by the dashed line in figure 3. An example of the inverted signal from high pass filtered pressure is shown in figure 4.

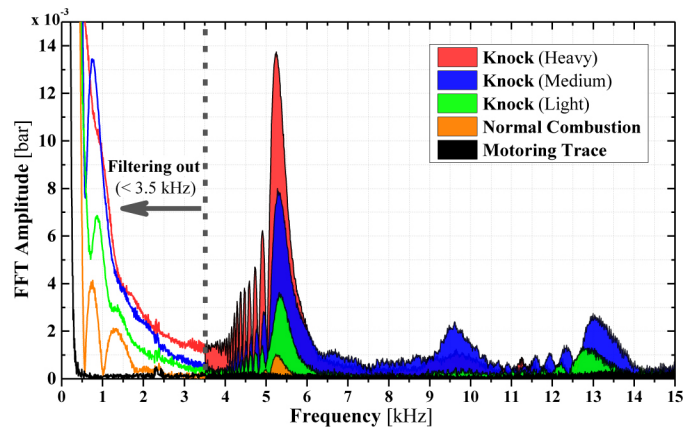


Figure 3. FFT amplitude and cut-off frequency: various cycles from motoring to heavy knock. (Gasoline only, $\lambda=1.00$, intake pressure = 1.2 bar, varied spark timing)

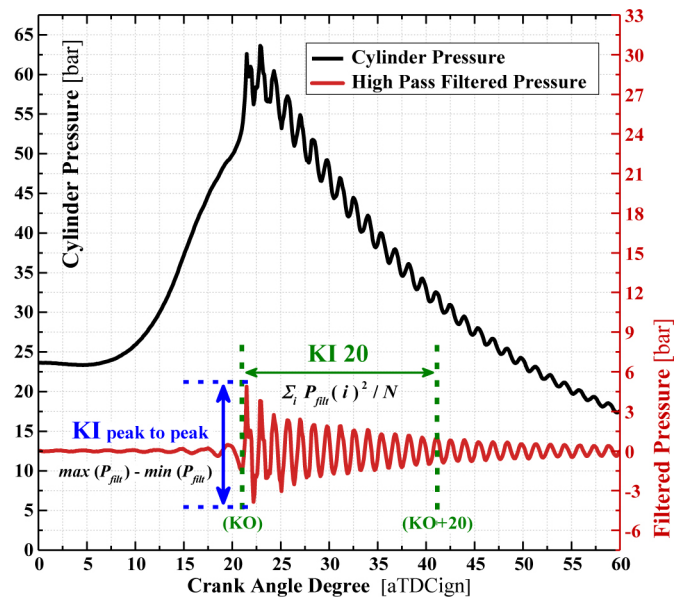


Figure 4. Heavy knock cylinder pressure (top, black line) and filtered pressure (bottom, red line). (Gasoline only, $\lambda=1.00$, intake pressure = 1.2 bar, spark timing 13° bTDC)

Knock Index (KI)

Knock intensity characterization methods are various and there is no conventional guideline to measure knock. The most commonly used methods are categorized by the domains of FFT; time and frequency. Time domain based intensity can be divided into peak basis single intensity and peak and duration integrated intensity. Also, the frequency domain based intensity is normally linearly correlated to the time domain based intensity, but it has an additional benefit which is

the ability to find a dominant frequency range on the frequency domain [22,23]. The time domain basis peak and energy index and frequency domain basis PSD (Power Spectral Density) analysis are described below.

Peak Basis Index

Among the peak intensity measuring methods, two indices are commonly used; MAPO (Maximum Amplitude of Pressure Oscillations) and $KI_{\text{peak to peak}}$ (pressure difference between maximum peak and minimum peak of the filtered pressure). The MAPO index involves the absolute value of filtered pressure data and choosing the peak value in a knock occurring window [24,25]. In contrast, the $KI_{\text{peak to peak}}$ is the difference between maximum peak and minimum peak values.

In this study, $KI_{\text{peak to peak}}$ is used for the peak basis intensity calculation. As shown by the vertical blue arrow in figure 4, the difference from the maximum to minimum peak of filtered pressure is calculated using equation 2.

$$KI_{\text{peak to peak}} = |(\max\{p(i)\}) - (\min\{p(i)\})| \quad (2)$$

In equation 2, $p(i)$ indicates the filtered pressure and the ' i ' is crank angle degree value. The range of ' i ' is set from -20 TDC_{ign} to +70 TDC_{ign}, this is to avoid noise from other sources such as intake and exhaust valve closing signals; signal oscillation caused by the valve closing is occasionally higher than knocking oscillation in lower knocking cycle cases.

Energy Basis Index

The peak basis intensity above is simple to calculate, but there is a drawback that such measurements could be affected by external noise. To address this concern, the signal energy basis intensity is also used to measure knock [26,27]. The common name of the energy basis intensity is SEPO (Signal Energy of Pressure Oscillations), and the SEPO method takes the average value of the square of the filtered pressure from the onset of knock to a given point of crank angle degree. The range of crank angle degree used by researchers varies, but a typical range is from 5 to over 20 crank angle degree.

Konig et al. [28] suggested an energy basis knock intensity method which is measured over a 20 crank angle degree range, that is called 'KI 20'. The KI 20 measurement is adopted in this study, and the detailed calculation is shown in equation 3, and illustrated in figure 4.

$$KI\ 20 = \frac{1}{N_{\text{samp}}} \sum_{i=1}^{N_{\text{samp}}} (P(i) - P_{\text{mean}})^2 \quad (3)$$

In equation 3, P_{mean} is the average pressure value – zero level of the high-pass filtered data and N_{samp} is the number of pressure samples within the 20 degree crank angle range following the offset of the first pressure pulse. The pressure data are measured per 0.1 crank angle degree, so there are 200 data points for every 20 crank angle degrees, and N_{samp} is 200 in this experiment.

Power Spectral Density Analysis

The frequency domain can be also used to measure knock intensity. Two most commonly used methods are FFT amplitude spectrum analysis, shown in figure 3, and PSD analysis. The advantage of the frequency domain analysis is the ability to find the peak frequency. The benefit of the PSD method is the ability to make an overall intensity comparison, regardless of the signal frequency.

Relation between Peak and Energy Index

Both the peak and energy basis indices are calculated and compared in order to determine a proper knock quantification index. First, the comparison between EGR and air dilution is carried out. Figure 5 demonstrates the relation between peak basis intensity ($KI_{\text{peak to peak}}$) and energy basis intensity (KI 20). The green round symbols are air dilution data while the blue diamond symbols indicate EGR dilution, and the dilution cases show no noticeable difference.

To examine the relation between the two knock indices, a regression equation is performed based on the combined air and EGR dilution data. When the polynomial regression is obtained without restrictions, the KI 20 is linear to 2.14th order of $KI_{\text{peak to peak}}$ and the origin of $KI_{\text{peak to peak}}$ corresponds to a negative value of KI 20 (-0.0046 bar²). But considering the meaning and units of each knock index (bar and bar²), the equation form is set to a second order polynomial equation and forced to pass through the origin (0, 0).

$$KI\ 20 = 0.0285 \times (KI_{\text{peak to peak}})^2 ; R^2 = 0.9643 \quad (4)$$

Equation 4 is the result of the final regression equation between KI 20 and $KI_{\text{peak to peak}}$ with proper restrictions. The coefficient of determination (CoD, denoted by R^2) of the $KI_{\text{peak to peak}}$ basis KI 20 regression is 0.9643. Meanwhile, the CoD of KI 20 basis $KI_{\text{peak to peak}}$ intensity is 0.843.

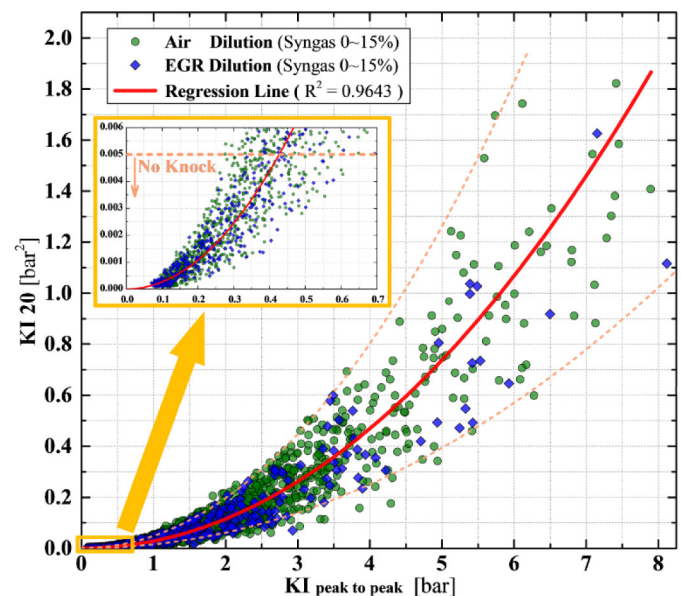


Figure 5. The relation between peak intensity ($KI_{\text{peak to peak}}$) and energy intensity (KI 20) under lean air and EGR dilution conditions.