

Methanol Fuel Testing on Port Fuel Injected Internal-Only EGR, HPL-EGR and D-EGR® Engine Configurations

Eric Randolph, Raphael Gukelberger, Terrence Alger, Thomas Briggs,
Christopher Chadwell, and Antonio Bosquez Jr.
Southwest Research Institute

ABSTRACT

The primary focus of this investigation was to determine the hydrogen reformation, efficiency and knock mitigation benefits of methanol-fueled Dedicated EGR (D-EGR®) operation, when compared to other EGR types. A 2.0 L turbocharged port fuel injected engine was operated with internal EGR, high-pressure loop (HPL) EGR and D-EGR configurations. The internal, HPL-EGR, and D-EGR configurations were operated on neat methanol to demonstrate the relative benefit of D-EGR over other EGR types. The D-EGR configuration was also tested on high octane gasoline to highlight the differences to methanol. An additional sub-task of the work was to investigate the combustion response of these configurations. Methanol did not increase its H_2 yield for a given D-EGR cylinder equivalence ratio, even though the H:C ratio of methanol is over twice typical gasoline. Although the methanol H_2 reformat yield did not increase over gasoline for a given equivalence ratio, the total yield did increase due to an extended rich misfire limit of the dedicated cylinder. Methanol-fueled D-EGR extended the maximum load of the engine by 2 bar BMEP. It also improved CoV of IMEP, increased dilution tolerance, improved combustion efficiency, and improved thermal efficiency. Cooled EGR also suppressed hot spot pre-ignition of methanol.

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INTRODUCTION

China is heavily pursuing energy independence via multiple pathways, one of which is coal-derived methanol. Chinese engine manufacturers are also pursuing methods to reform methanol to fast burning H_2 and high octane CO for improving engine cold start, dilution tolerance and efficiency.

To further enhance efficiency, engine manufacturers can use cooled EGR and apply these reformation methods to introduce fast-burning H_2 into the cooled EGR loop to expand the EGR dilution limits. EGR can further improve knock tolerance, though the dilution tolerance of the engine limits the degree of improvement. To take advantage of the knock mitigation of EGR and further enhance efficiency with methanol, high compression ratio may be utilized.

There are many methods to reform methanol [1], including partial oxidation of low-pressure loop EGR (LPL-EGR), catalytic decomposition, and steam reformed LPL-EGR. Many of these reformation methods are unproven, either fundamentally or in commercialization. Additionally, some of the methods may require additional on-vehicle infrastructure for hydrogen production and storage that is unconventional in the automotive world.

Dedicated EGR is an engine concept which is used to deliver cooled EGR and reform hydrocarbon fuels into CO and H_2 [2]. D-EGR is not a deviation from modern engine design; rather, D-EGR is a shift

in the basic configuration and operating regime of the engine that actively reforms fuel on an as-needed basis. Therefore, it requires no additional on-vehicle infrastructure or significant deviation in engine hardware that may be perceived as unconventional.

The D-EGR concept dedicates one or more cylinders of the engine to delivering EGR. These are called the dedicated cylinders because the entire exhaust content is routed to the intake. They are operated fuel-rich, which reforms part of the fuel to H_2 and CO through partial oxidation. This reformat increases dilution tolerance through improved flame speed, and knock tolerance because of the high RON of H_2 and CO [2,3]. Further, the faster laminar burning velocity of methanol [4] could sustain higher levels of dilution in the engine. It could also extend the rich misfire limit in the dedicated cylinder, increasing reformat production.

$$OI = RON - K * (RON - MON) \quad (1)$$

In an engine designed specifically to operate on methanol, the attributes of the fuel can be leveraged to increase efficiency. Figure 1, coupled with equation 1, shows that modern engine designs favor fuels with high RON and low MON. This is also supported in a plurality of literature [7,9,10,11,12] and is largely due to effort to increase efficiency through higher specific loads, lower pumping speed, higher compression ratio and lower charge air temperatures.

Table 1 shows the octane index of HEEE to be 99.8 when using an octane weighting factor of -0.33. Neat methanol's octane index is higher due to both a higher RON and large sensitivity, which results in the fuel behaving like a fuel with higher RON. This attribute of methanol can further be used to increase efficiency through increased compression ratio (fundamental to increasing efficiency).

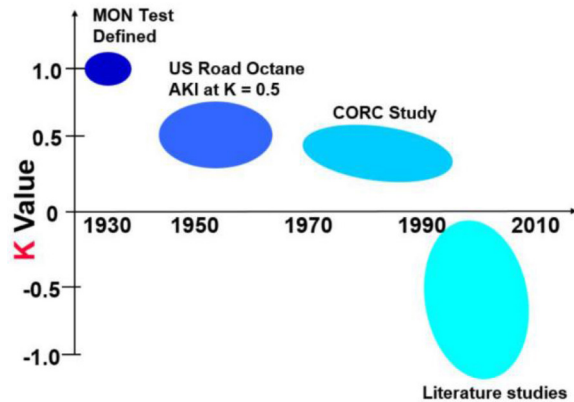


Figure 1. Historical Octane Index Weighting Factor, K [7]

Table 1. Test Fuel Properties

Fuel	HEEE	Neat methanol
H:C ratio	1.86	4
LHV [MJ/kg]	42.89	20.0
MON	88.6	89
RON	97.0	109
Sensitivity	8.4	20
OI @ K=-0.33	99.8	115

EXPERIMENTAL SETUP

A 2.0 L turbocharged inline four-cylinder engine was used for this study as outlined in Table 2. The engine was equipped with intake and exhaust cam phasers. The stock compression ratio of the engine was 9.5:1, but to take advantage of the knock abatement afforded by D-EGR, the tests were conducted at a compression ratio of 12:1. This also made it well suited for methanol. Fuel was delivered through a multipoint port fuel injection system. A SwRI Dual-Coil Offset (DCO®) high ignition energy system was used [15,16], with 5 DCO re-strikes resulting in ignition energy of ~450 mJ.

Table 2. Engine Specification

Displaced volume	1998 cc
Stroke	86 mm
Bore	86 mm
Compression ratio	12:1
Number of cylinders / valves	4 inline / 16
Maximum power	203 kW @ 5500 rpm
Maximum torque	353 Nm @ 1700-5500 rpm
Injection	Multi-point sequential

Four test setups were used (Table 3), comprised of three engine configurations: internal EGR only, 25% HPL-EGR, dedicated EGR and two different fuels (Table 1): neat methanol and Haltermann E0 Tier II certification gasoline (HEEE). The test used the same engine long block, boosting system, ignition and fuel system. The configurations were facilitated by hardware changes on the engine by changing the intake and exhaust routing.

Table 3. Test Setups

Engine configuration	Fuel
Internal EGR	Methanol
25% cooled EGR	Methanol
D-EGR	HEEE
D-EGR	Methanol

Valve phasing was set to maximize internal residuals within the combustion stability limit of 3% CoV IMEP, with the valve overlap centered at TDC. For conditions where over-scavenging was possible, an exhaust oxygen concentration of less than 1% was an additional constraint.

Internal EGR, represented schematically in Figure 2, was configured by routing the dedicated exhaust to the main exhaust after the turbine and capping off the flow path to the intake. With internal EGR, the mass of trapped residuals was established by cam phasing.

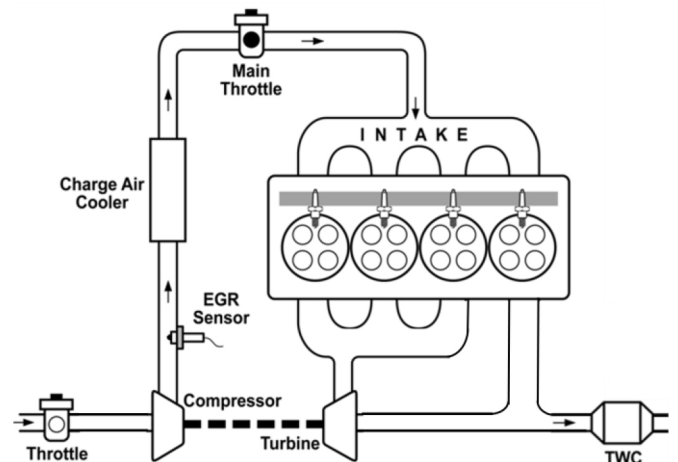


Figure 2. Turbocharged 4-Cylinder Internal EGR Configuration

The 25% HPL-EGR and D-EGR configuration is shown schematically in Figure 3. For these configurations, one cylinder was used to produce EGR and is referred as the dedicated cylinder or D-cyl. The other cylinders are referred to as the main cylinders. 25% HPL-EGR was tested by running the dedicated cylinder stoichiometric; no reformat was present, which separated the impact of the EGR dilution from the fuel reformation. Cam timing for these configurations was set in a similar method to that described for the internal EGR configuration. The dedicated cylinder fueling was controlled with feedback from a UEGO in the EGR loop. The dedicated cylinder exhaust was cooled and then routed to a mixer to

promote even mixing of the EGR to all four cylinders (Figure 3). The EGR-fresh air mixture temperature was controlled with an intercooler downstream of the mixer.

Spark advance was adjusted to MBT (CA50 6-8° aTDC) or knock limited spark advance (KLSA). Fuel flow was measured with a Coriolis flow meter. Direct gas analyzers were used to measure CO, HC, NO_x, CO₂ and O₂ from a heated sample line.

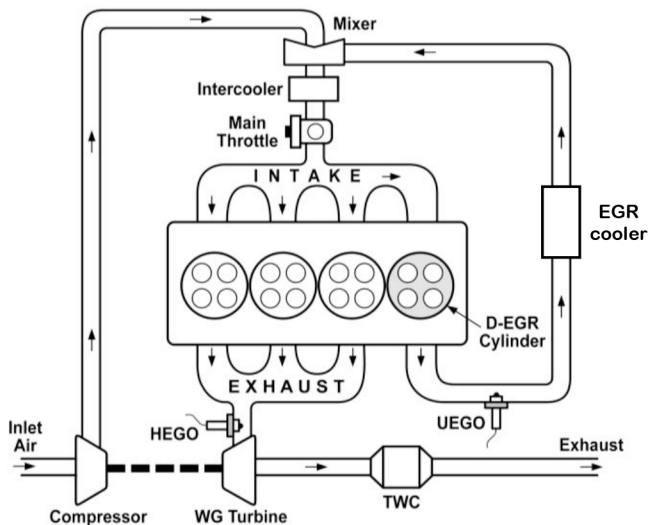


Figure 3. Turbocharged 4-Cylinder in 25% HPL / D-EGR Configuration

RESULTS AND DISCUSSION

The following section outlines predicted and actual hydrogen reformation of the dedicated cylinder, dedicated cylinder enrichment limits, load sweep results and hot-spot pre-ignition.

Hydrogen Reformation

Hydrogen reformate production was predicted through an empirical analysis and then compared to actual results.

Predicted Hydrogen Reformation Yield

The engine was run in the D-EGR configuration on HEEE fuel at 1500 rpm and 10 bar BMEP to establish a baseline hydrogen yield. Hydrogen was sampled from the dedicated cylinder exhaust three times per data point and analyzed by a gas chromatograph.

The H₂ yield rate was linear with the dedicated cylinder equivalence ratio (D-phi) and yielded a rate slightly greater than 1% H₂ per 10% enrichment. Both observations were consistent with measurements on HEEE observed in [5]. The study carried out in [5] examined H₂ yield rate for ethanol blends, which found that some fuels' H₂ production had a rough correlation to H:C ratio of the fuel blends that were tested. Although [5] showed some inconsistencies for H₂ yield rate as a function of H:C, a model was developed for methanol H₂ yield rate and the results are shown in Figure 4.

The prediction made several assumptions, including that the empirical water-gas shift equilibrium constant K was similar to gasoline, at roughly 3.5-3.8 [6]. This reaction is characterized by

equations 2 and 3, where equation 2 defines K as a function of the mole fraction of CO, H₂O, CO₂ and H₂. Equation 2 is the water-gas shift (WGS) reaction, which calculates the equilibrium concentration of water in the exhaust stream, where y is the H:C ratio of the fuel. It can be seen from these equations that for a given equivalence ratio, if both the ratio of CO:CO₂ are similar and the ratio of H₂O:H₂ is similar between two fuels, then the fuel with higher H:C ratio will yield more H₂.

$$\frac{x_{CO} * x_{H_2O}}{x_{CO_2} * x_{H_2}} = K \quad (2)$$

$$x_{H_2O} = 0.5 * y * \frac{x_{CO_2} + x_{CO}}{\frac{x_{CO}}{K * x_{CO_2}} + 1} \quad (3)$$

Based on the increased H:C ratio of methanol (4:1), the hydrogen yield rate was estimated to be over 2% per 10% dedicated cylinder fuel enrichment (Figure 4).

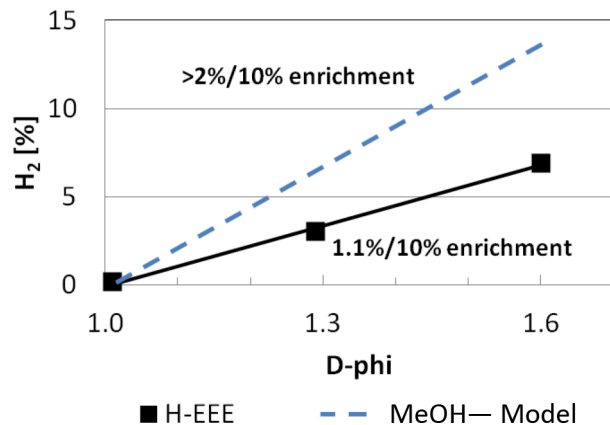


Figure 4. HEEE and Predicted Methanol H₂ Yield

Actual Hydrogen Reformation Yield

The engine was operated on neat methanol in the D-EGR configuration and the actual hydrogen yield was similar to HEEE. The slope was slightly steeper, with methanol producing 1.2% per 10% enrichment versus HEEE producing 1.1% per 10% enrichment (Figure 5).

This result differs significantly from the predicted value using the commonly accepted equilibrium constant for the water-gas shift (WGS) reaction (characterized by equilibrium reactions shown in Equation 4). To determine the source of discrepancies between the predicted and actual H₂ yield, the inputs to the WGS equation were reviewed. The WGS equilibrium constant was found to be higher for methanol at slightly greater than 4, which is consistent with a lower H₂ yield rate. The value was calculated for HEEE as well, which was found to be consistent with [6] at 3.5. Based on the calculated K, the exhaust water fraction was calculated for each fuel (Figure 6). The water fraction for methanol was found to more than double that of HEEE, which is consistent with the expectation based on the increased in H:C ratio. Based on this observation, CO and CO₂ were reviewed.