

Impact of EGR Quality on the Total Inert Dilution Ratio

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ABSTRACT

A series of tests were performed on a gasoline powered engine with a Dedicated EGR[®] (D-EGR[®]) system. The results showed that changes in engine performance, including improvements in burn rates and stability and changes in emissions levels could not be adequately accounted for solely due to the presence of reformat in the EGR stream. In an effort to adequately characterize the engine's behavior, a new parameter was developed, the Total Inert Dilution Ratio (TIDR), which accounts for the changes in the EGR quality as inert gases are replaced by reactive species such as CO and H₂. By calculating the TIDR and using this factor, rather than the reformation ratio or EGR rate, the results of the testing and sources of combustion improvement in the engine can be segregated into improvements due to the presence of reformat, such as initial kernel formation periods and unburned hydrocarbon emissions, and improvements due to the reduction in the total inert dilution levels, such as the emissions of the oxides of nitrogen and the fully turbulent combustion period.

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INTRODUCTION

Cooled and uncooled exhaust gas recirculation (EGR) have been used for many years in the transportation industry. Initially, EGR was introduced for diesel engines to reduce the amount of engine-out oxides of nitrogen (NO_x) emissions [1, 2]. For the same purpose, uncooled EGR was also used on gasoline engines in the 1970's through 1990's, although at relatively low concentrations ($\leq 10\%$). In more recent years, the application of cooled EGR to gasoline engines has become more prevalent as a means to improve engine efficiency and reduce emissions [3, 4]. One particular embodiment of cooled EGR is an engine technology called Dedicated EGR. A Dedicated EGR engine uses specific cylinder(s) dedicated to EGR production (Figure 1) such that the dedicated cylinder's exhaust is fully separated from the tailpipe exhaust and utilized as the sole EGR source for the engine. The greatest significance of this architecture resides in the ability to operate the dedicated cylinder(s) at air-to-fuel ratio (AFR) other than stoichiometric, while a three-way catalyst can continue to be used in the tailpipe. The resulting EGR gas composition provides improved combustion characteristics for the entire engine. A schematic of a generic four-cylinder configuration is shown in Figure 1.

As a consequence of being able to run the dedicated cylinder at any AFR desired, while maintaining stoichiometric conditions in the tailpipe, the D-EGR engine has the capability of changing the "quality" of the exhaust gas that is recirculated. Many factors can go into

changing the quality of the EGR. The exhaust gas of an ideal engine operating on a stoichiometric mixture of fuel and air consists only of the inert gases N₂, CO₂ and H₂O [5]. However, in an actual engine, inhomogeneous mixture preparation and fuel-to-combustion chamber interaction can lead to unburned hydrocarbons (HC), excess oxygen (O₂), and particulate emissions. Furthermore, various temperature and pressure conditions, as well as the short combustion time scales, can limit the combustion kinetics and result in unburned or partially oxidized fuel. Fuel selection can also have a strong influence on exhaust gas composition. For instance, the use of alternative, low-carbon fuels, such as natural gas, is considered to be an effective measure to reduce CO₂, particulate matter (PM) and NO_x emissions [6]. Finally, the equivalence ratio has a major impact on the concentration of emissions components. On the lean side of stoichiometric combustion, CO, CO₂ and H₂O are decreasing while O₂ levels are increasing. On the rich side of stoichiometric combustion, CO and H₂ steadily increase while CO₂, O₂ and H₂O decrease [7]. In either direction, once the exhaust begins to deviate from stoichiometric, the level of reactive species (O₂, H₂, CO) versus inert species (CO₂, H₂O) changes. As a result, changes in the exhaust gas composition can affect combustion characteristics for the entire engine.

When the D-EGR cylinder is operating rich, partially burned combustion products are routed back to all cylinders for consumption. Through the in-cylinder reformation process of rich hydrocarbon

combustion, high levels of carbon monoxide (CO) and diatomic hydrogen (H₂) are produced. Increased levels of these constituents in the intake charge improve flame speed and combustion speeds, reduce unburned hydrocarbon (HC) emissions, and increase knock tolerance for the entire engine. Compared to a conventional, stoichiometric EGR engine, the combination of an increase in knock resistance of the fuel / reformat mixture and an increase in EGR rate enables either an increase in compression ratio or an expansion of the operating range at optimum combustion phasing. In addition, higher levels of EGR, enabled by the burn rate increases and improved stability, reduce the thermal and pumping losses compared to stoichiometric EGR [8, 9, 10]. Overall, the use of D-EGR roughly doubles the potential efficiency improvement of an engine when compared to stoichiometric EGR.

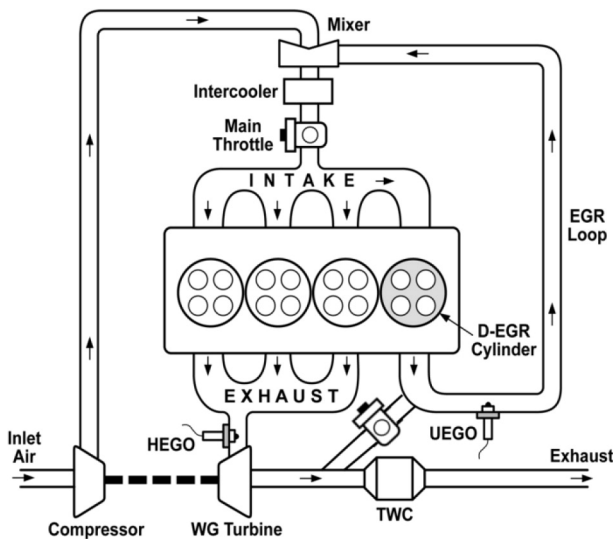


Figure 1. Schematic of a 4-cylinder engine in D-EGR configuration with EGR bleed-off valve

Unfortunately, excessively rich combustion has not been nearly as well studied and documented as combustion in lean and stoichiometric conditions. In particular, explaining the changes in engine performance parameters as the equivalence ratio in the EGR loop changes is a challenge. The goal is to determine what level of change or improvement is attributable to the change in EGR quality and how much is attributable to other factors. This work examined how rich combustion in the D-EGR cylinder(s) will impact EGR quality by altering the inert and reactive specie concentrations. To enable direct comparisons in the performance of various dilution concepts, a common parameter was established with TIDR. This was necessary since a comparison with the conventional, intake CO₂ based EGR rate provided deficient results. The conventional approach to calculating the EGR rate, on a volume basis, is as follows

$$EGR_rate = \frac{CO_{2_Intake}}{CO_{2_Exhaust}} \times 100$$

(1)

where CO₂_intake and CO₂_exhaust are the CO₂ concentrations measured in the intake manifold and exhaust manifold, respectively. This study will demonstrate why this approach is not adequate for a D-EGR engine and will outline and propose an alternative calculation.

EXPERIMENTAL SETUP

This study has been carried out on a turbocharged, inline four cylinder 2.0 L engine with port fuel injection. The engine was equipped with intake-only variable camshaft phasing. In its baseline configuration, a peak torque of 300 N-m was reached starting at 2250 rpm and maximum power delivery was 135 kW at 5500 rpm. One measure of the engine modifications for this work included the replacement of the production turbo charger with a dual-scroll unit designed for a 1.6 L engine to account for the change in boosting requirements due to EGR dilution [12]. Additionally, a high energy ignition system was employed. The system was a continuous discharge ignition system and could operate in single strike, multi strike, or DCO mode. The level of primary ignition energy, re-strike offset, and amount of re-strikes could be adjusted. A more detailed description can be found in previous publications [13, 14]. The ignition system was always operated in DCO mode and the ignition energy was controlled to ~400 mJ. The stock compression ratio of 9.1:1 was increased to 13.5:1. Table 1 gives a description of the relevant physical parameters of the engine in stock form.

Table 1. Base engine specification

Displaced volume	1998 cc
Stroke	93 mm
Bore	82.7 mm
Connecting Rod	144 mm
Compression ratio	9.1:1
Number of cylinders / valves	4 in line / 16
Maximum power	135 kW @ 5500 rpm
Maximum torque	300 Nm @ 2250 rpm
Injection	Multipoint sequential

A configuration of the D-EGR concept is shown in the schematic in Figure 1. For these tests, an EGR bleed-off valve was installed, which allowed variations in the EGR rate.

Haltermann's EEE certification gasoline was used for all engine testing. The fuel had a lower heating value (LHV) of 42.89 MJ/kg, an Anti knock Index (AKI) of 92 and a hydrogen-to-carbon ratio of 1.862.

RESULTS AND DISCUSSIONS

This study was separated into a simulation and engine experiment part. As part of the initial work, a series of engine simulations on a DEGR engine were performed to characterize the intake manifold composition with varying rates of enrichment in the dedicated cylinder.

Characterization of D-EGR Intake Concentrations and their Related Properties

The important difference between D-EGR and LPL EGR is that the EGR composition can be altered, relieving the D-EGR engine from the typical constraint that the diluents must be compatible with the engine aftertreatment system. This section examines the impact that the A/F ratio in the D-EGR cylinder had on the EGR composition and subsequent intake composition. It was also noted during this work that the conventional metric for EGR was insufficient when comparing D-EGR to other EGR systems. Prior studies [8, 10, 15] have shown that a 25% D-EGR engine behaved much differently than a 25% LPL EGR engine and that the amount of reformat in the DEGR changed combustion in a manner that did not trend simply with reformat levels. The reason for this was found to be the changing composition of the EGR and the impact the individual constituents had on combustion. A modification to the dilution calculation is provided to assist comparing different dilution strategies on a common basis.

Simulation Work

To characterize the total dilution levels on a D-EGR engine and to enable comparisons to a LPL EGR configuration, 1-D simulations were conducted to document the dedicated cylinder exhaust and intake concentrations for D-EGR engine operation. The motivation for this work grew from the recognition that the EGR in a D-EGR engine contained both inert and reactive fractions. Part of the reactive fraction was H_2 , which has a very wide flammability limits. A sub-task of this investigation was to understand at what point the intake charge becomes flammable (that is a backfire hazard).

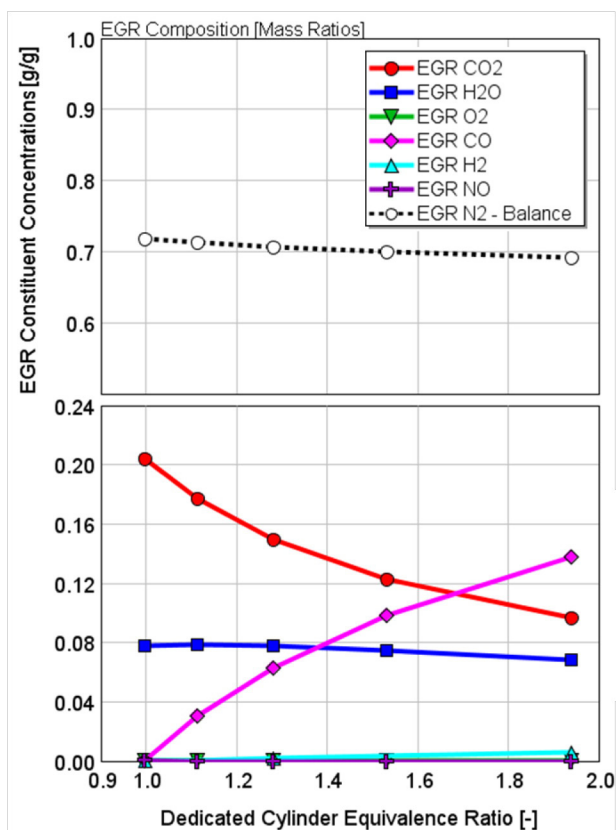


Figure 2. D-EGR concentrations (mass fraction) as a function of 25% ϕ_{D-EGR}

The composition of the exhaust from the dedicated cylinder is shown in Figure 2 (mass basis) and Figure 3 (molar basis) as a function of the equivalence ratio in the dedicated cylinder (ϕ_{D-EGR}). These results are based on 1-D simulation, with the model having been validated using engine data. For this simulation work, indolene was chosen as the fuel. The important fuel specifications for this study were the lower heating value (LHV) of 43.94 MJ/kg and the H/C ratio of 1.866. The inlet air was assumed to be dry.

Figure 3 shows how inert constituents (H_2O , CO_2 , and N_2) are replaced with reactive constituents (CO , H_2) as the D-EGR cylinder was operated at higher equivalence ratios. The simulations were run beyond the nominal flammability limit of gasoline (defined as stable combustion while running 25% EGR and rich) to complete the trends. However, recent results using novel operating techniques have shown that ϕ_{D-EGR} of ~ 1.8 or more are possible. It should also be noted that as the dedicated cylinder equivalence ratio increased, the amount of water vapor in the EGR stream decreased from $\sim 13\%$ to $\sim 10\%$ at $\phi = 1.5$. While this decreased the level of diluents in the exhaust gas, it also served to change the dew point of the mixture. These results agreed quite well with other results from previous publications [8].

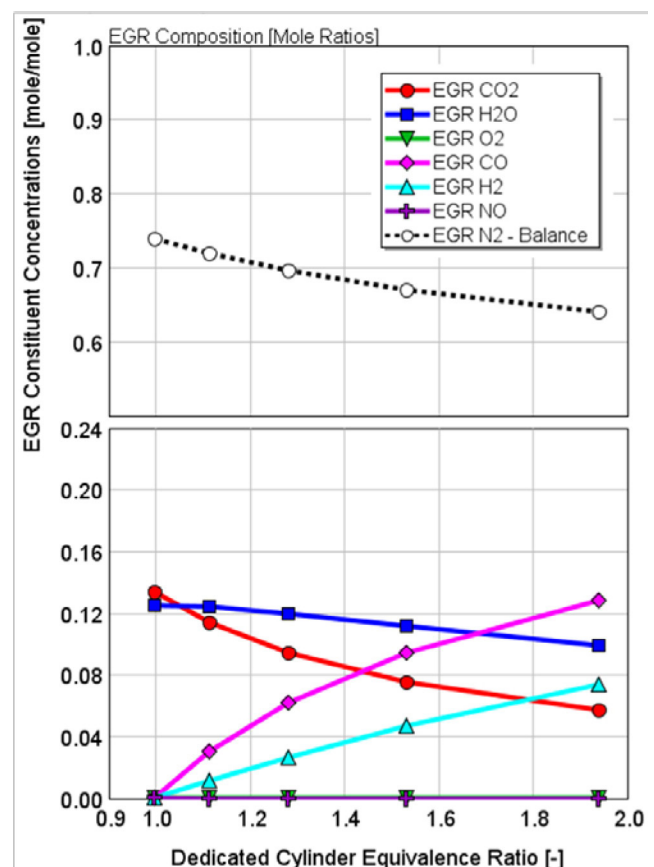


Figure 3. D-EGR concentrations (mole fraction) as a function of 25% ϕ_{D-EGR} [16]

The measurement location of the results from the simulations shown in Figure 2 and Figure 3 was then moved to the intake plenum. A general trend of the intake concentrations as a function of ϕ_{D-EGR} is shown in Figure 4 and Figure 5. As the D-EGR cylinder is run rich (in a 25% D-EGR hardware configuration) the inert dilution of the fuel air mixture decreased proportionally as

CO and H₂ increased and H₂O and CO₂ decreased. Thus, the EGR went from being a completely (or nearly completely) inert substance to being a mostly inert substance with some reactive components. Therefore, there is the possibility that some of the combustion changes with increasing ϕ_{D-EGR} [8, 10] could be attributed to the lower levels of diluent in the inducted charge, while other changes are attributed to the increased H₂ and CO concentrations. The relative importance of the different parameters (total dilution level vs. concentration of H₂ and CO) will be examined in the latter portion of this report.

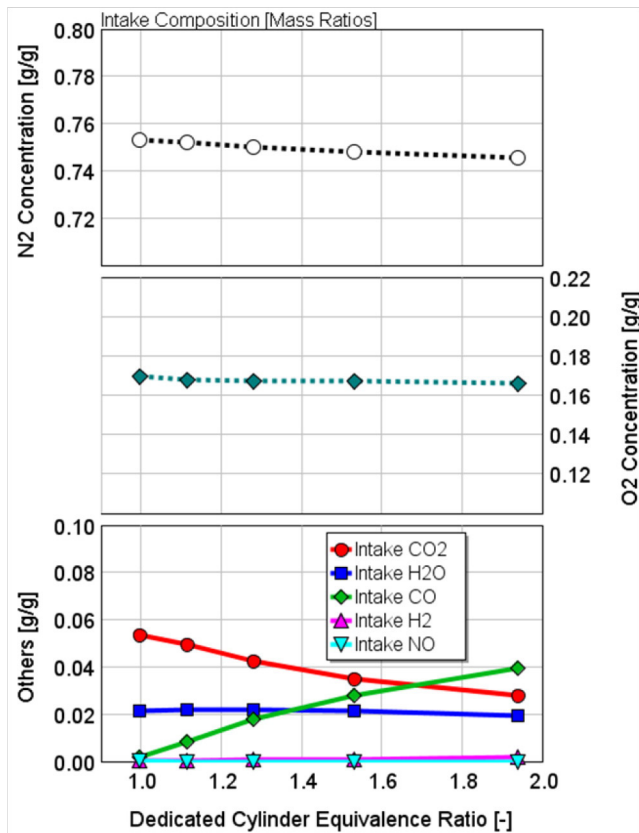


Figure 4. Intake concentrations (mass ratios) as a function of 25% ϕ_{D-EGR}

The total dilution level of the inducted charge, whether that dilution comes from ambient air (N₂+H₂O) or re-circulated exhaust gas (N₂+H₂O+CO₂), can have either beneficial or harmful effects (or sometimes both) on an SI engine. Depending on the type of dilution, the engine can become more efficient and more knock resistant, but also suffer from slower burn rates and reduced stability. Since the majority of dilution is N₂, the magnitude of the dilution is thought to be more significant than the concentrations or origins of the inert constituents. Other than impacting the temperature of the charge, the source of the EGR, whether through an external EGR system or incylinder sources via the cam phasing system, appears to be immaterial with respect to its impact on performance. Thus, for control purposes it may be more appropriate to model total inert dilution in the inducted charge and not specifically estimate EGR flow. In addition, the development of the D-EGR concept, or the use of reformer catalysts in the exhaust loop, means that the composition of the EGR can change considerably and therefore change the impact

of EGR on knock, burn rate and other parameters. For future systems of this nature, understanding the total dilution ratio as well as the concentration of any reactive species may be required.

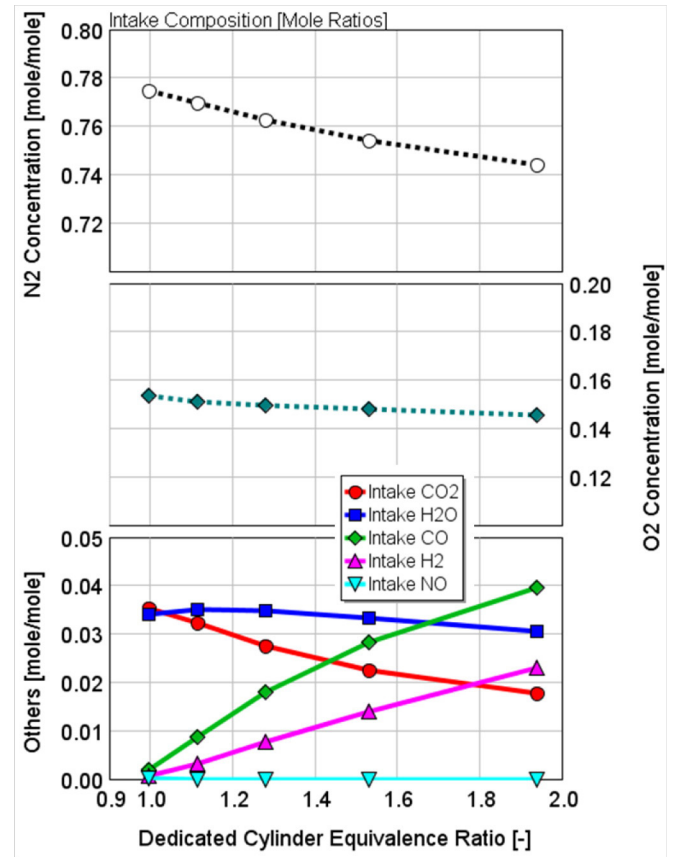


Figure 5. Intake concentrations (mole ratios) as a function of 25% ϕ_{D-EGR} [16]

With known intake concentrations, a common basis for diluted engines was selected to be the total inert dilution ratio (TIDR). TIDR was defined as the total inert dilution of O₂ in the intake (before fuel injection). The calculation in (2) uses the mass fractions of the inert constituents N₂, CO₂, and H₂O as well as the mass fraction of oxygen in the engine intake manifold.

$$TIDR = \frac{X_{N_2-in} + X_{CO_2-in} + X_{H_2O-in}}{X_{N_2-in} + X_{CO_2-in} + X_{H_2O-in} + X_{O_2-in}} \quad (2)$$

The relationship between LPL EGR and D-EGR in terms of TIDR is shown in Figure 6. The graph on the left hand side displays the linear increase of TIDR with greater EGR rates for a conventional LPL EGR system. The graph on the right hand side shows a decrease in TIDR when the D-EGR cylinder was enriched (assuming the 4 cylinder configuration for the D-EGR engine), which is consistent with the reduction in CO₂, H₂O and N₂ mole fractions shown in Figure 5. At a $\phi_{D-EGR} = 1.0$, the results show that the D-EGR engine is representative of a standard, external EGR configuration (either LPL or HPL), while operation at $\phi_{D-EGR} \approx 1.5$ reduced the TIDR by an equivalent EGR rate decrease of approximately 2%, which reflects the shift from stoichiometric EGR, with nearly 100% diluents to a rich mixture of diluents and reactive compounds.