Developing Simulation Strategies for Mixed-Mode Combustion Engines

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Objective

It is established that fuels with high octane numbers (RON & MON) and high sensitivities (S = RON-MON) are resistant to engine knock. This allows for high engine compression ratios (CR), resulting in higher efficiencies.

Our objective is to simulate the effect of lean, mixed-mode combustion on engine efficiency for various fuels. Figure 1 below compares the energy release behavior in stoichiometric and mixed-mode combustion. Stoichiometric combustion utilizes turbulent deflagration, while mixed-mode combustion uses deflagration and end-gas autoignition within the cylinder, hence the two peaks shown in Figure 1.

Figure 2 below shows efficiency gains with respect to a standard engine and fuel operating stoichiometrically at CR=9, as well as hypothetical efficiency gains at lean combustion shown with arrows [1]. Lean operation can improve efficiency by lowering peak temperatures within the engine.

An ideal (knock-free) engine simulation was developed in the GT-Power simulation program. Resulting data was written into the EPA's ALPHA vehicle simulation for performance testing, as a baseline for this objective. This strategy will be applied in the future to determine the effect of mixed-mode combustion in vehicle engines. These efforts will support a DOE objective of determining an optimal combination of octane numbers, CR, and use of mixed-mode combustion.

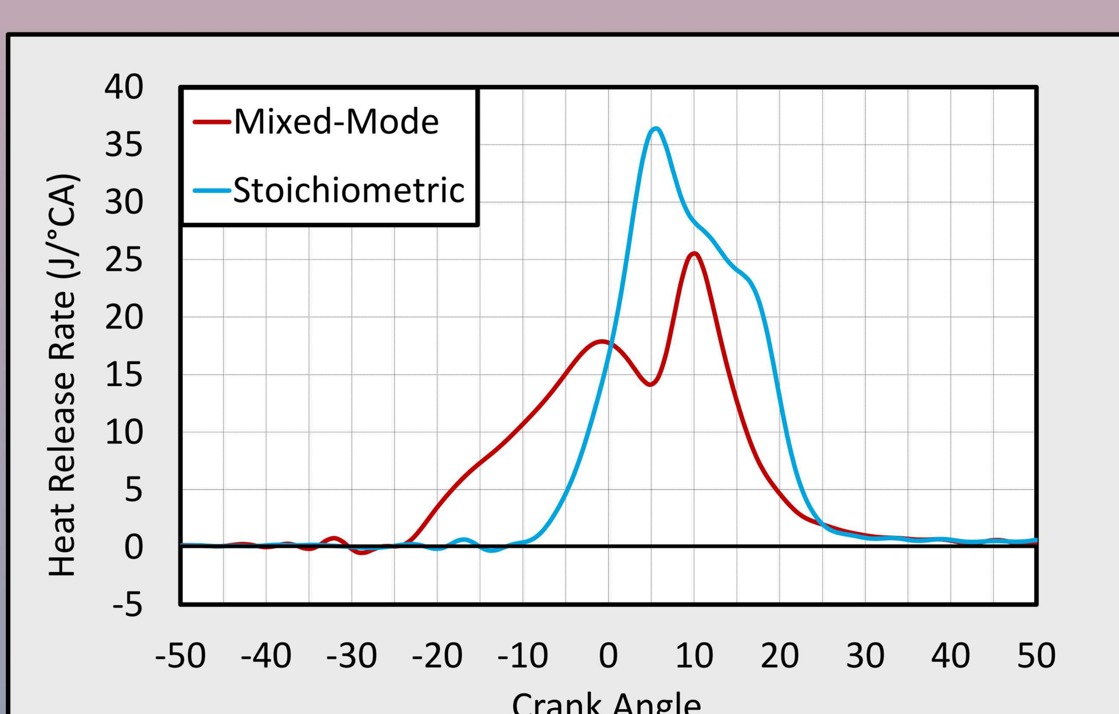

Figure 1: Contrast of stoichiometric and mixed-mode combustion

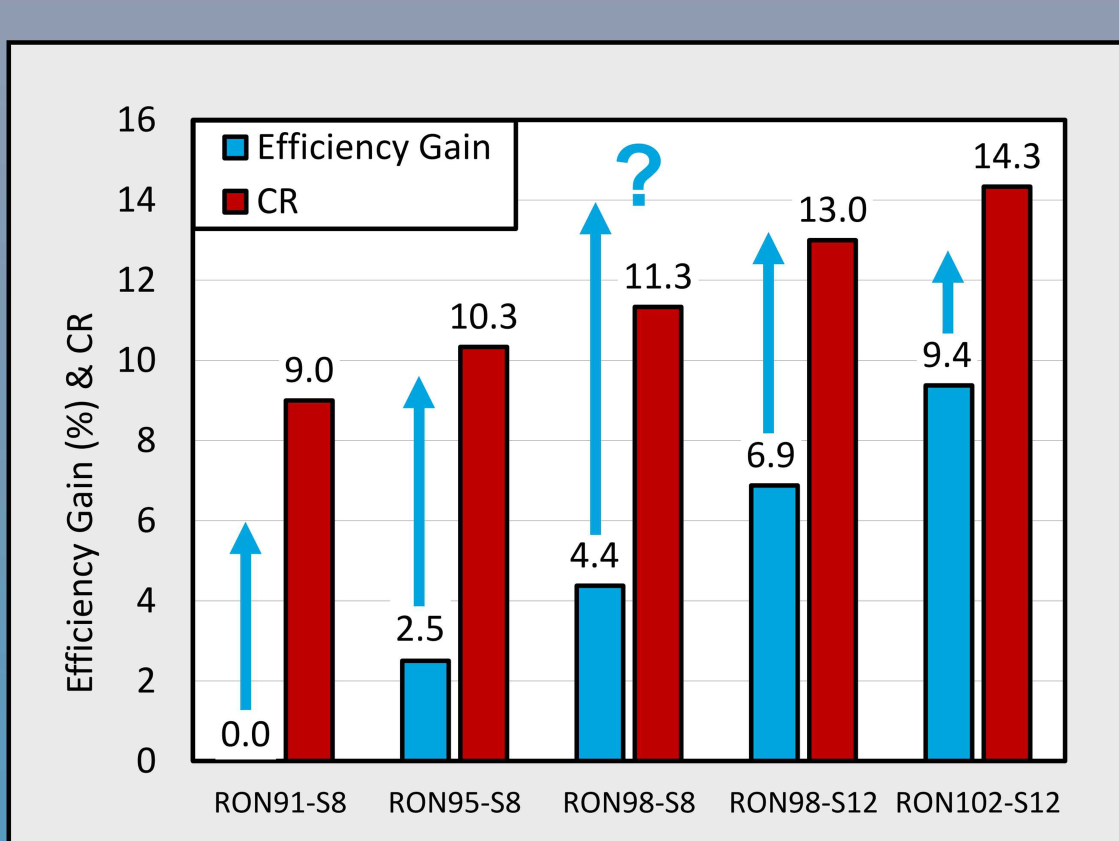

Figure 2: Experimental efficiency gains with stoichiometric combustion and hypothetical efficiency gains for lean combustion

ALPHA Simulation

The EPA's ALPHA program is a full-vehicle drive cycle simulation that takes into account engine parameters such as torque and fuel consumption, as well as vehicle parameters, such as velocity, mass, and friction.

ALPHA requires an input of a map that describes fuel consumption as a function of engine speed and load.

ALPHA simulates a dynamic vehicle and calculates relevant efficiency parameters, such as MPG. Figure 3 in the next column shows two drive cycles in ALPHA over a speed-load map.

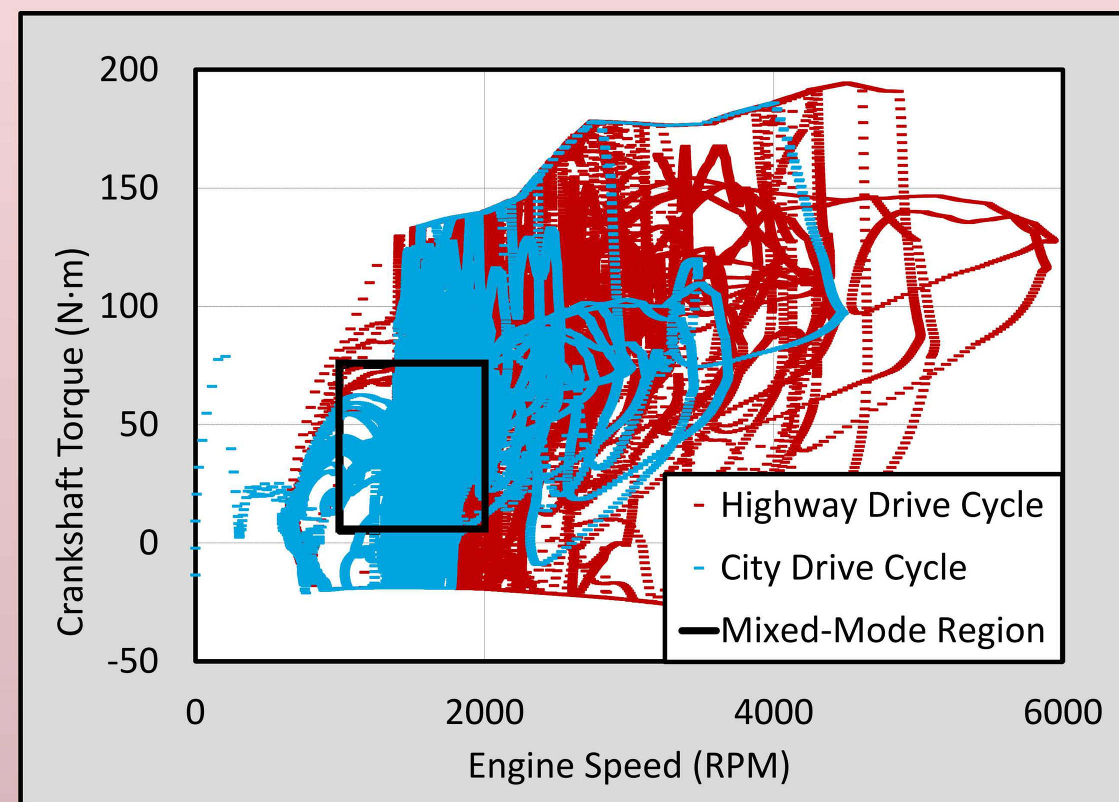

Figure 3: ALPHA drive cycles

GT-Power Simulation

A single-cylinder engine simulation was designed to be replicative of many lab-scale engines.

Input variables include parameters such as the following:

- Fuel chemistry
- Cylinder stroke, bore, and CR
- Ambient conditions
- Combustion phasing
- Stoichiometry
- Engine speed

GT-Power is capable of running parametric studies to vary several inputs in a single study.

GT-Power Simulation Results

GT-Power simulations return information relating to the engine's performance such as torque, pumping/friction losses, fuel consumption rate, etc. Without knock constraints, this ideal model utilizes an optimal combustion phasing of CA50=10°, meaning that 50% of the fuel charge has burned within 10° of crankshaft rotation from the start of the power-stroke.

Data from GT-Power is critical to determining engine efficiency and efficiency gains with different CR values and different fuels, as this data is called by ALPHA.

Figure 3 below shows a fuel consumption map produced by GT-Power, and is the type of map required by ALPHA. This represents an ideal case in which knock is not considered.

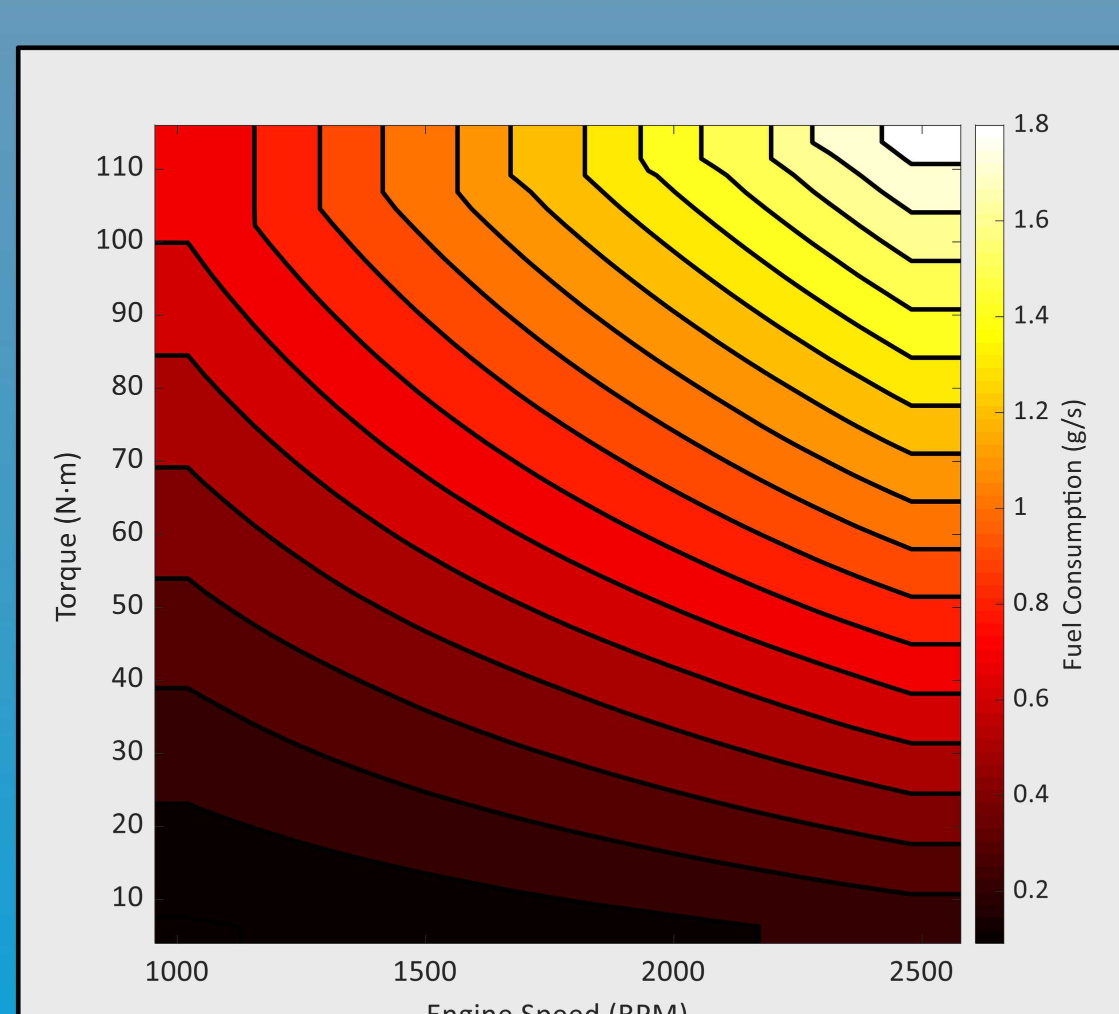

Figure 4: Fuel consumption map produced by GT-Power, assuming ideal, non-knock limited engine behavior

ALPHA Simulation Results

With the fuel consumption data from GT-Power, ALPHA can simulate various city and highway drive cycles to determine vehicle performance.

Key results from ALPHA include mileage, fuel consumption, and CO_2 emissions.

Figure 5 below shows the results from ALPHA across various compression ratios, based on the ideal GT-Power fuel consumption data. The percentage of efficiency gain is with respect to the CR=8 result.

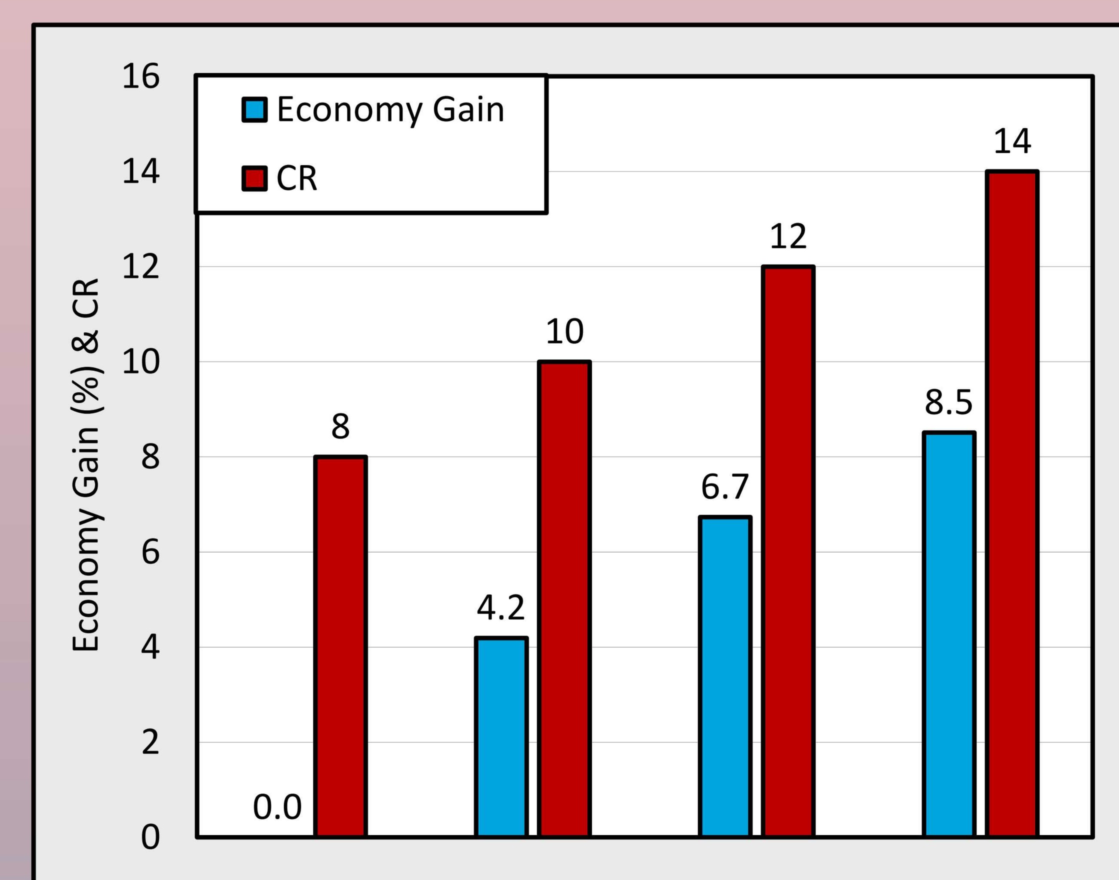

Figure 5: Baseline vehicle efficiencies by compression ratio, assuming non-knock limited engine behavior

Conclusions and Further Work

The results from ALPHA based on the simulation in GT-Power show a positive correlation between CR and efficiency, which matches the experimental data in Figure 2.

The large fraction of the time that ALPHA cycles spend in low speed/load settings motivates future simulation of lean combustion (see the "Mixed-Mode Region" in Figure 3).

Subsequent simulations will incorporate a knock model as well as knock-resistant fuels. Figure 6 below shows the combustion phasing in a simulation with a preliminary knock model. Note the retarded combustion phasing at lower speeds and higher loads. The retarded combustion phasing is necessary at knock-limited conditions, however, this lowers the work-extraction efficiency of the engine.

After such improvements, the process developed in this study will be utilized to determine efficiency gains and optimal octane numbers for advanced, mixed-mode engines that employ both stoichiometric and lean combustion.

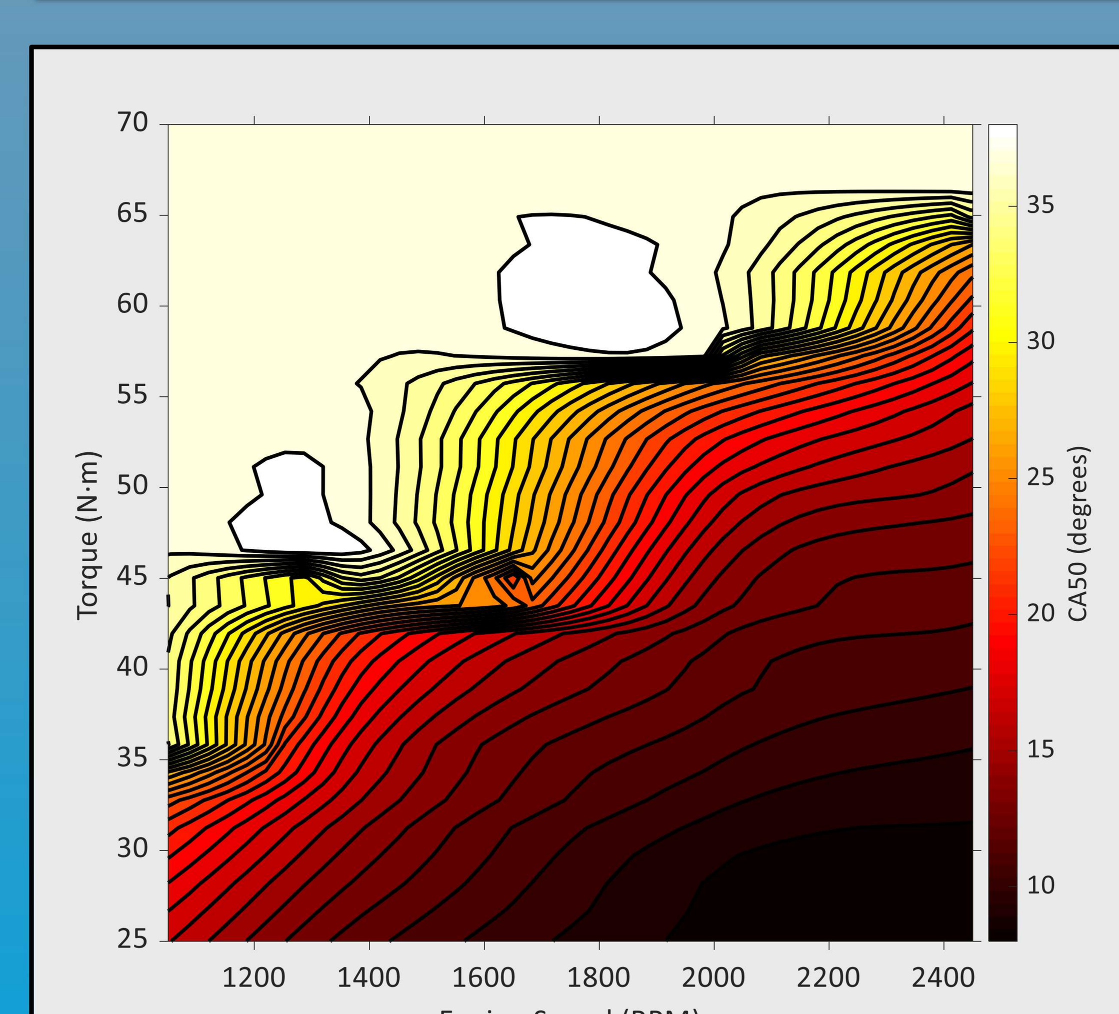

Figure 6: Combustion phasing map produced by GT-Power with a basic knock model incorporated

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[1] Miles, Paul, "Efficiency Merit Function for Spark Ignition Engines: Revisions and Improvements Based on FY16–17 Research." Technical Report. U.S. Department of Energy, Washington, DC. 2018. DOE/GO-102018-5041.