A Numerical Study of the Effects of Fuel Injection Timing on the Performance and Emission Characteristics of a Natural Gas Spark Ignition Direct Injection Engine

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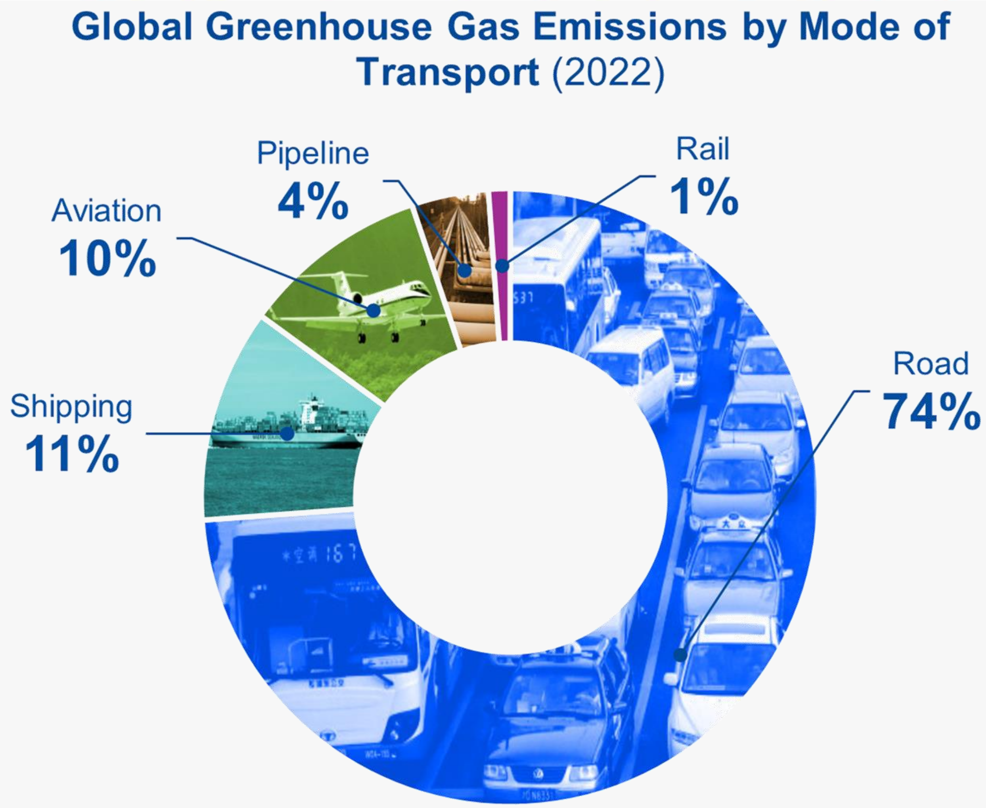
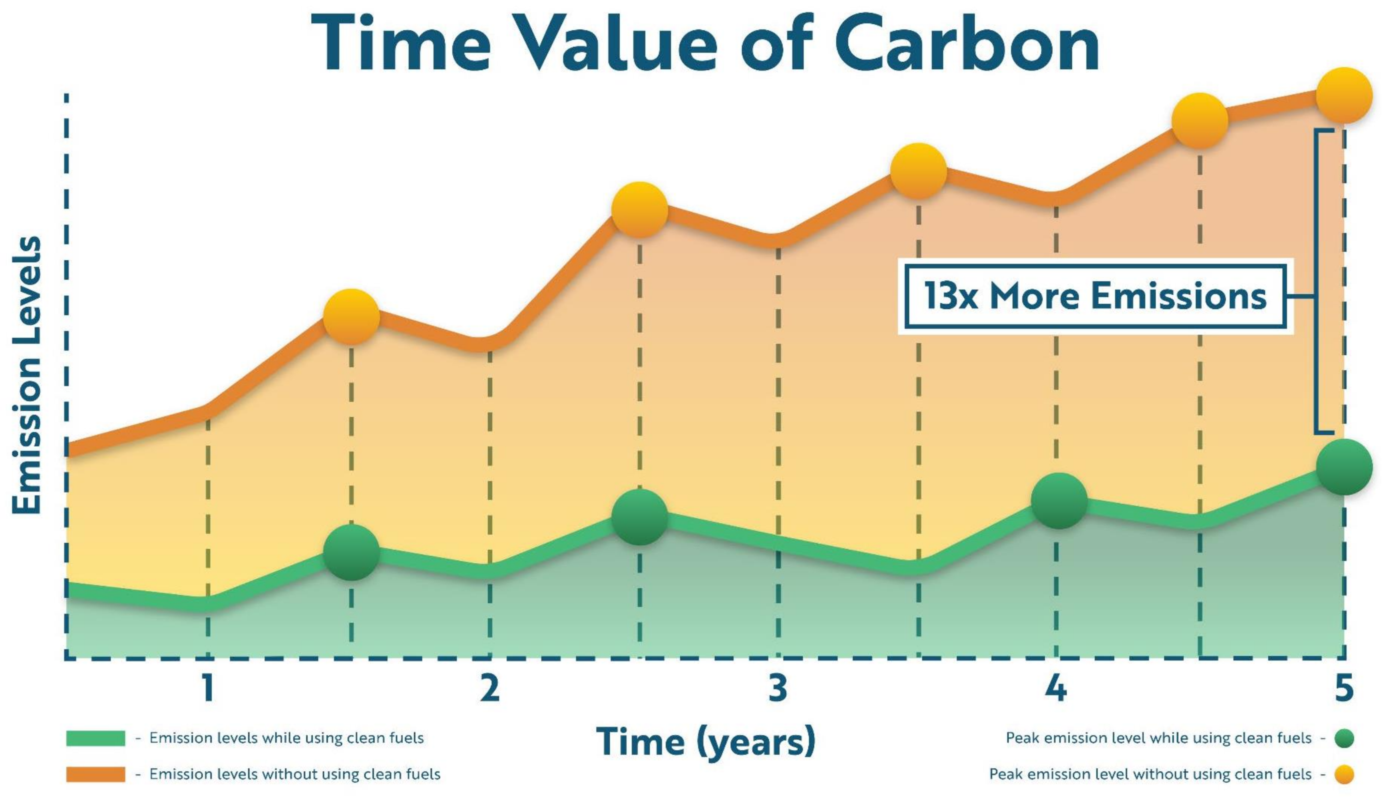
The Promise of Natural Gas

- Conventional vehicles are a major contributor to climate change
- A sudden leap to electric vehicles is unlikely given the lack of infrastructure and resources globally
- The world faces a race against time to halt the production of greenhouse gases
- Natural gas can provide an immediate reduction in emissions. It is cheap and abundantly available in Nigeria



Source: International Energy Agency, 2023

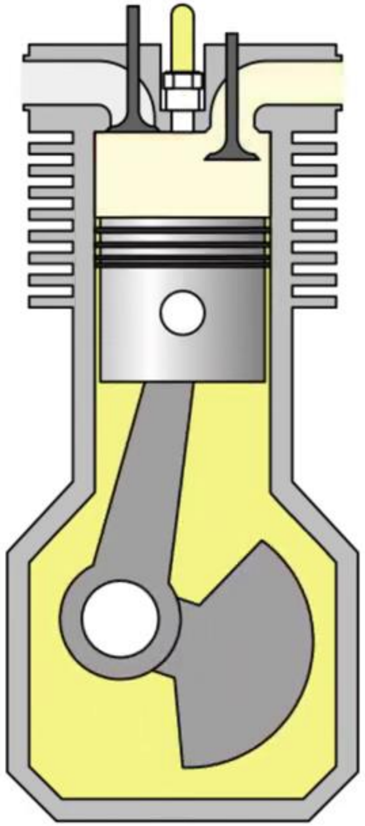
We Need to Act Now!



“A reduction in CO_2 emissions now can avoid decades of associated heating, thus having significantly more value than carbon reductions made later”

-Clean Fuels Alliance America

Primer: The Combustion Process



Current Understanding and Challenges

- Natural Gas is widely used in its compressed form (CNG)
  - Limitations:
    - CNG has a slow flame speed, and it requires a high ignition energy (Willems and Sierens, 2003)
    - CNG is lighter than air, it displaces air during mixing, resulting in lower volumetric efficiency and power output (Jahiru et al., 2010)
  - Resolution:
    - Increasing the compression ratio gives a fast-burning rate (Huang et al., 2008)
    - Direct injection of CNG improves the volumetric efficiency, and power (Tuner, 2016)
  - Outstanding Challenges:
    - In-cylinder activities during CNG combustion in direct injection engines are not well understood at a sub-scale level
    - The injection timing significantly influences CNG combustion (Aljamali et al., 2016) *– Optimal timing?*

Problem Statement

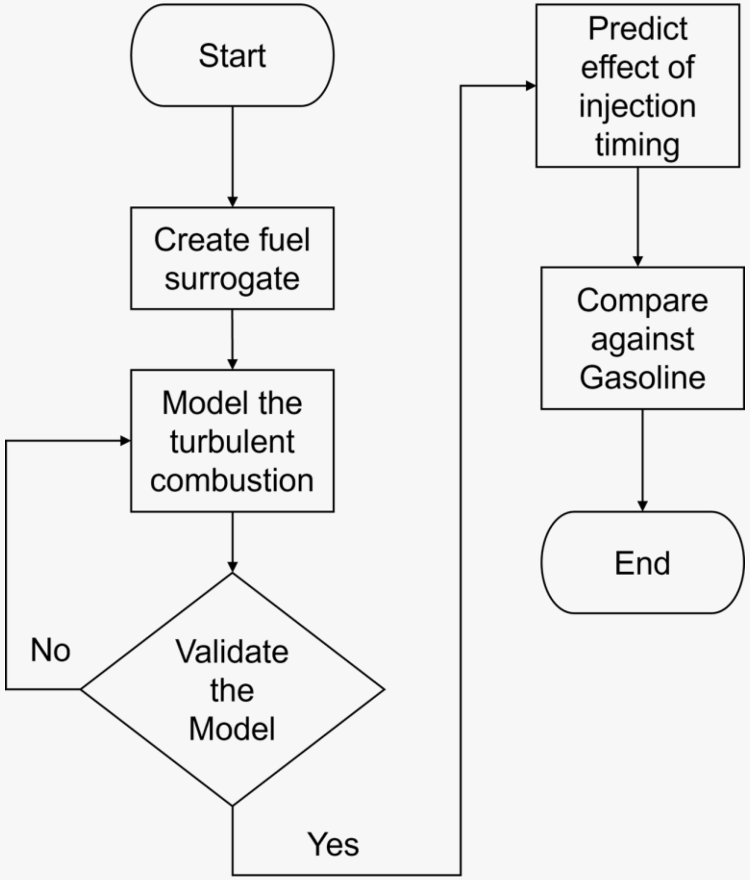
- It is essential to numerically investigate how injection timing influences the combustion of compressed natural gas in Spark Ignition Direct Injection (SIDI) engines

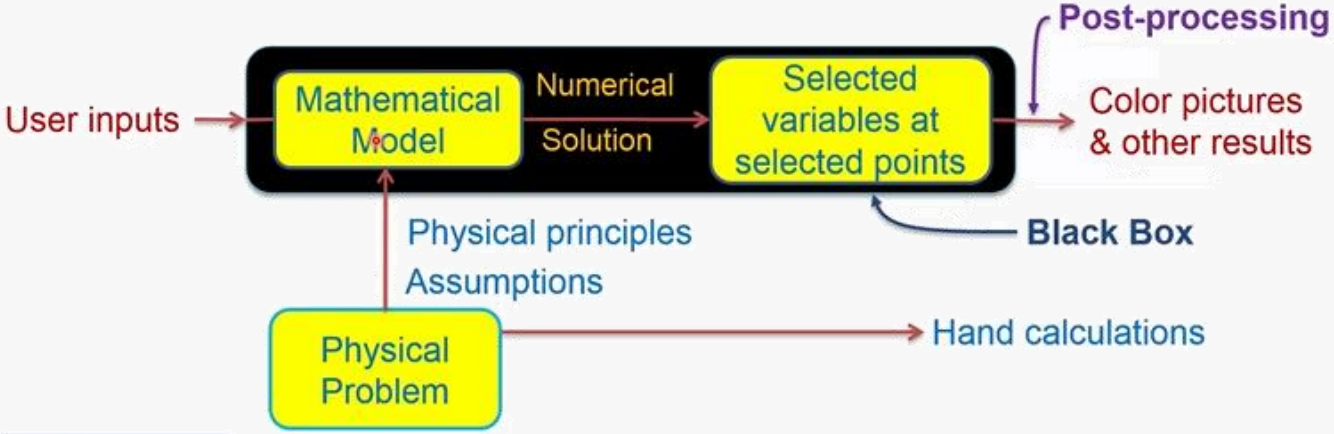
Specific Objectives

The objectives of this study are to:

1. Investigate the effects of early and late injections (relative to intake valve closure) on the combustion and emissions from a SIDI engine using a detailed 3-D computational fluid dynamic analysis
2. Evaluate the comparative performance of early and late injection relative to gasoline in a SIDI engine

Methodology: Overview





Source: Cornellx

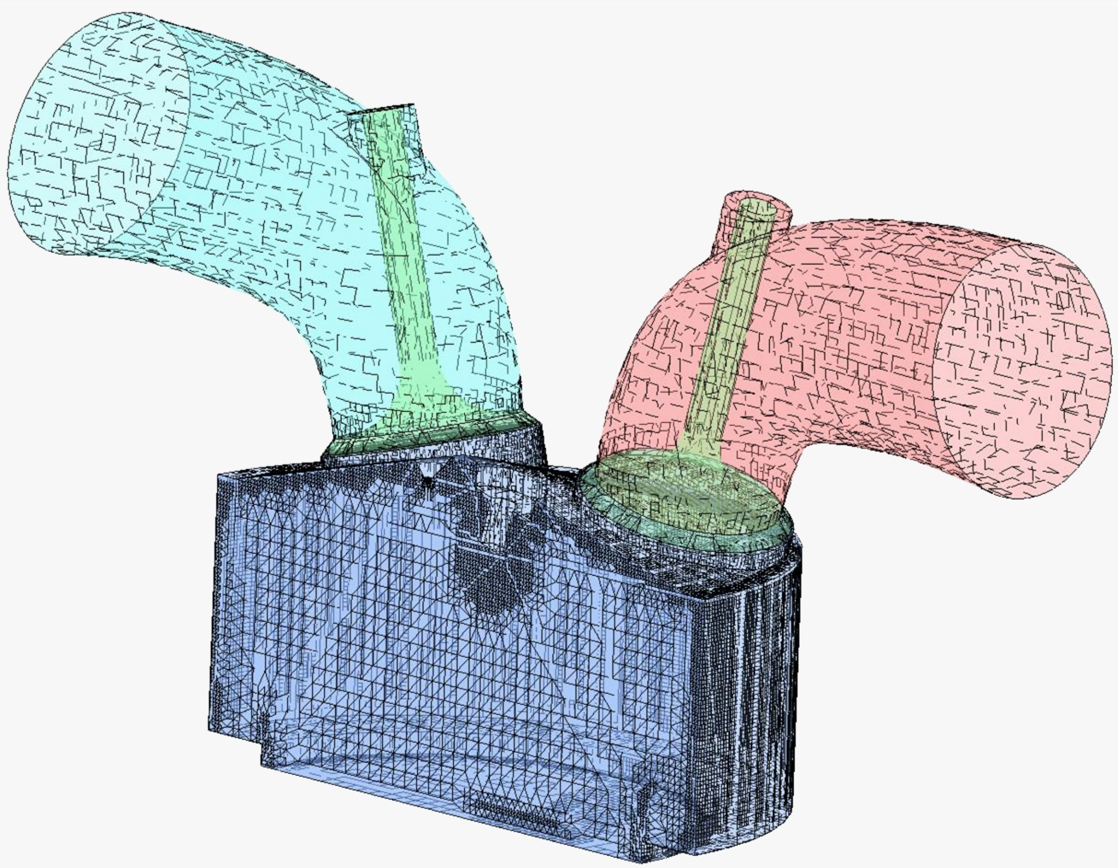
Chemistry Mechanism

- A multi-component fuel surrogate representing natural gas was created to account for the effect of fuel composition on combustion. Flame speed was estimated from a laminar flame speed lookup table
- Fuel effects were portrayed using the San Diego detailed reaction mechanism (UC San Diego, 2016) coupled with soot chemistry obtained from the Ansys Model Fuel Library (ANSYS Inc., 2024)
- A fuel mixture representing gasoline with 10% ethanol (E10) was created using a 4-component n-heptane/iso-octane/toluene/ethanol fuel surrogate.

Molar Composition of Natural Gas (Melaika et al., 2021)

Species	Molar Composition (%)
Methane	88.8
Ethane	6.0
Propane	2.5
Butane	0.6
Nitrogen	0.7
Carbon dioxide	1.4

Model Geometry



0.5 L AVL Single Cylinder Engine Specifications

Parameters	Value
Bore	8.2 cm
Stroke	9 cm
Connecting rod length	13.95 cm
Compression ratio	10:1
Number of valves	4

Governing Equations

MASS

$$\frac{\partial \overline{\rho}}{\partial t}+\nabla\cdot(\overline{\rho}\widetilde{\mathbf{u}})=\dot{\overline{\rho}}^{s}$$

SPECIES

$$\frac{\partial \bar{\rho}_{k}}{\partial t}+\nabla\cdot(\bar{\rho}_{k}\widetilde{\mathbf{u}})=\nabla\cdot\left[\overline{\rho}D\nabla\bar{y}_{k}\right]+\nabla\cdot\Phi+\dot{\bar{\rho}}_{k}^{c}+\dot{\bar{\rho}}_{k}^{s}\ \left(k=1,\cdots,K\right)$$

MOMENTUM

$$\frac{\partial \overline{\rho}\widetilde{\mathbf{u}}}{\partial t}+\nabla\cdot(\overline{\rho}\widetilde{\mathbf{u}}\widetilde{\mathbf{u}})=-\nabla\overline{p}+\nabla\cdot\overline{\boldsymbol{\sigma}}-\nabla\cdot\boldsymbol{\Gamma}+\overline{\mathbf{F}}^{s}+\overline{\rho}\mathbf{g}$$

ENERGY

$$\frac{\partial \overline{\rho}\tilde{I}}{\partial t}+\nabla\cdot\left(\overline{\rho}\widetilde{\mathbf{u}}\tilde{I}\right)=-\overline{p}\nabla\cdot\widetilde{\mathbf{u}}-\nabla\cdot\overline{\mathbf{J}}-\nabla\cdot\mathbf{H}+\overline{\rho}\widetilde{\varepsilon}+\dot{\overline{Q}}^{C}+\dot{\overline{Q}}^{S}-\dot{\overline{Q}}_{rad}$$

Spray source terms

Combustion source terms

Assumptions:

- Thermodynamic equation of state (ideal gas law)
- Newtonian fluid assumption
- Fick’s law of mass diffusion
- Fourier’s law of thermal diffusion

Mathematical Models

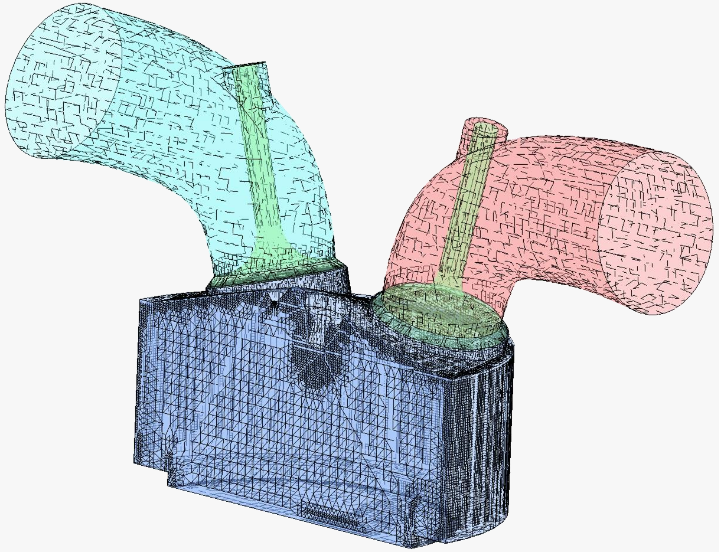
Phenomena	Models used
Momentum	Reynold's Averaged Navier-Stokes (RANS)
Turbulence	Re-Normalized Group theory (RNG) k-ε
Ignition kernel growth	Discrete Particle Ignition Kernel Flame (DPIK)
Flame propagation	G-equation

Boundary Conditions

- The turbulent “law of the wall” velocity condition and constant temperature boundary conditions were applied at all rigid walls in the computational domain to solve for near-wall shear stress and heat transfer.
    - The law of the wall condition sets the normal gas velocity equal to the normal wall velocity and defines the wall shear stress as: $\boldsymbol{\tau}_w = \rho(u^*)^2 \frac{\mathbf{v}}{|\mathbf{v}|}$
    - Convective heat flux through the walls was modelled using the Han and Reitz (1997) heat transfer model for a constant temperature boundary condition.
- Constant pressure of 1 bar was specified at the inlet and outlet boundaries
- An axis of symmetry boundary was applied on the face of the “cylinder symmetry”, taking advantage of the engine’s half-symmetrical geometry to reduce computational requirement, and extending calculations to the opposite face

Initial Conditions

- The engine case study was divided into three regions initialized in order: the intake region, the cylinder/primary region, and the exhaust region.



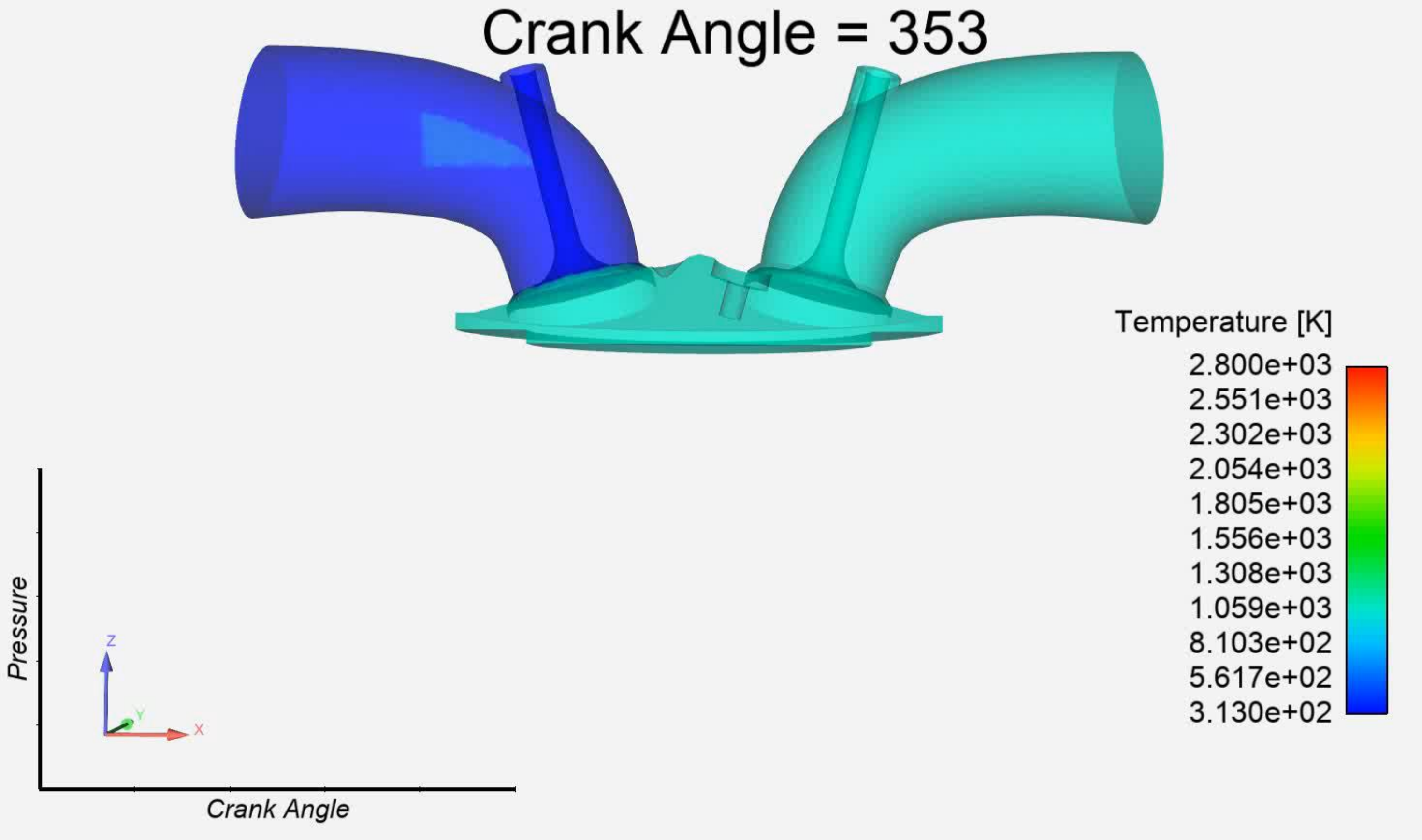
Initial Conditions at each Region of the Domain for CNG and (Gasoline)

Region	Initialization Order	Composition	Temperature (K)	Pressure (bar)
Intake	1	Air	313	0.85 (0.8)
Cylinder	2	EGR	1070	1.05
Exhaust	3	EGR	1070	1

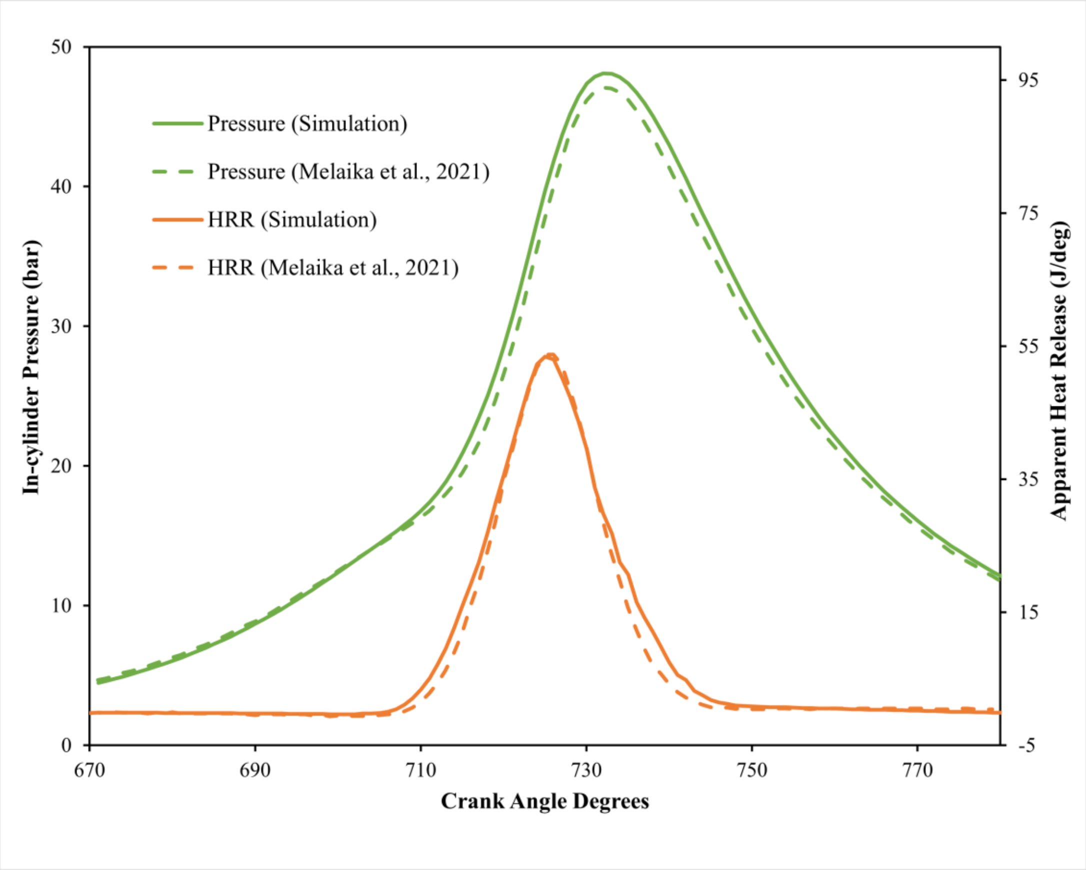
Solution Techniques

- The governing equations were spatially discretized based on a control volume approach. Fluid transport was discretized based on the Arbitrary-Lagrangian-Eulerian method
- A modified SIMPLE algorithm was used to solve the resulting algebraic equations and convection terms were solved using the quasi-second-order upwind method (ANSYS Inc., 2024)
- Chemistry was solved using the Ansys Forte chemistry solver and computational time was improved by applying the dynamic cell clustering method
- Transient engine simulation was performed for a 4-stroke engine at wide open throttle and stochiometric conditions, running at 2000 rpm between the intake valve open (IVO) and exhaust valve open (EVO)

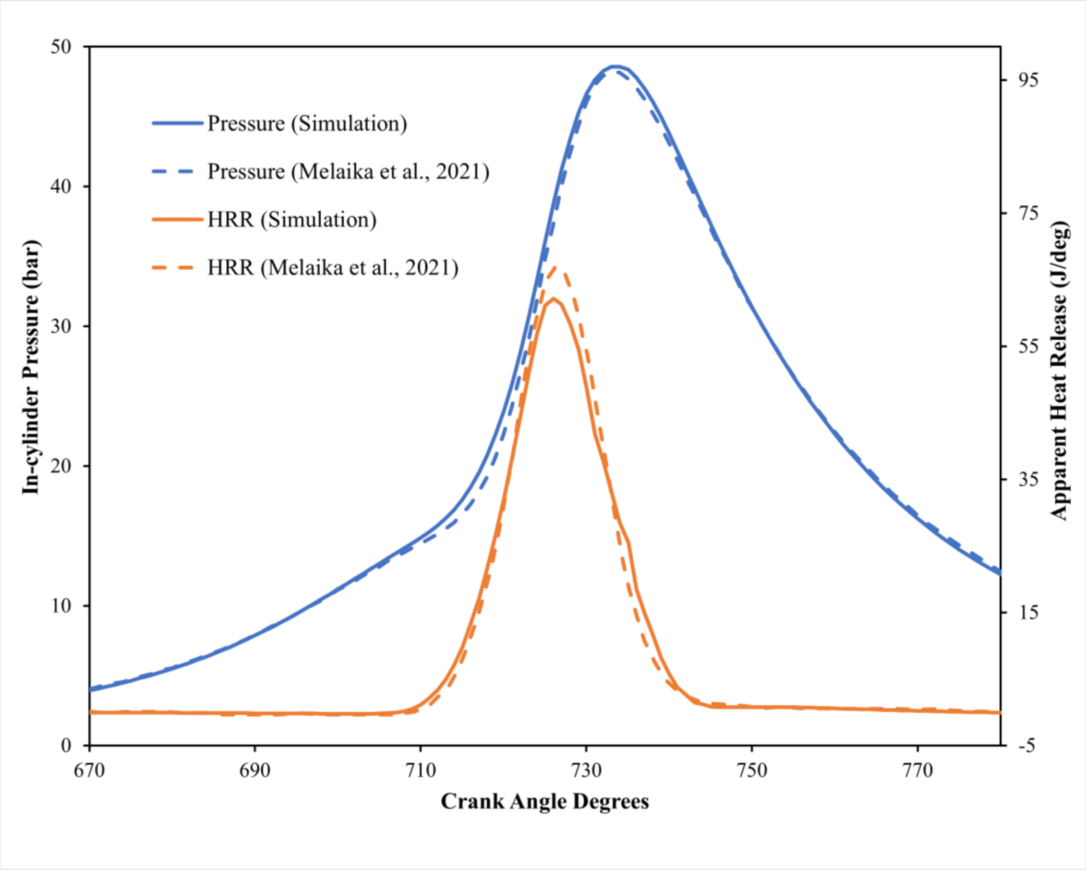
Visualizer


Crank Angle = 353
Temperature [K]
2.800e+03
2.551e+03
2.302e+03
2.054e+03
1.805e+03
1.556e+03
1.308e+03
1.059e+03
8.103e+02
5.617e+02
3.130e+02
Pressure
Crank Angle
Z
Y
X

Validation: Simulations are in agreement with the experimental results

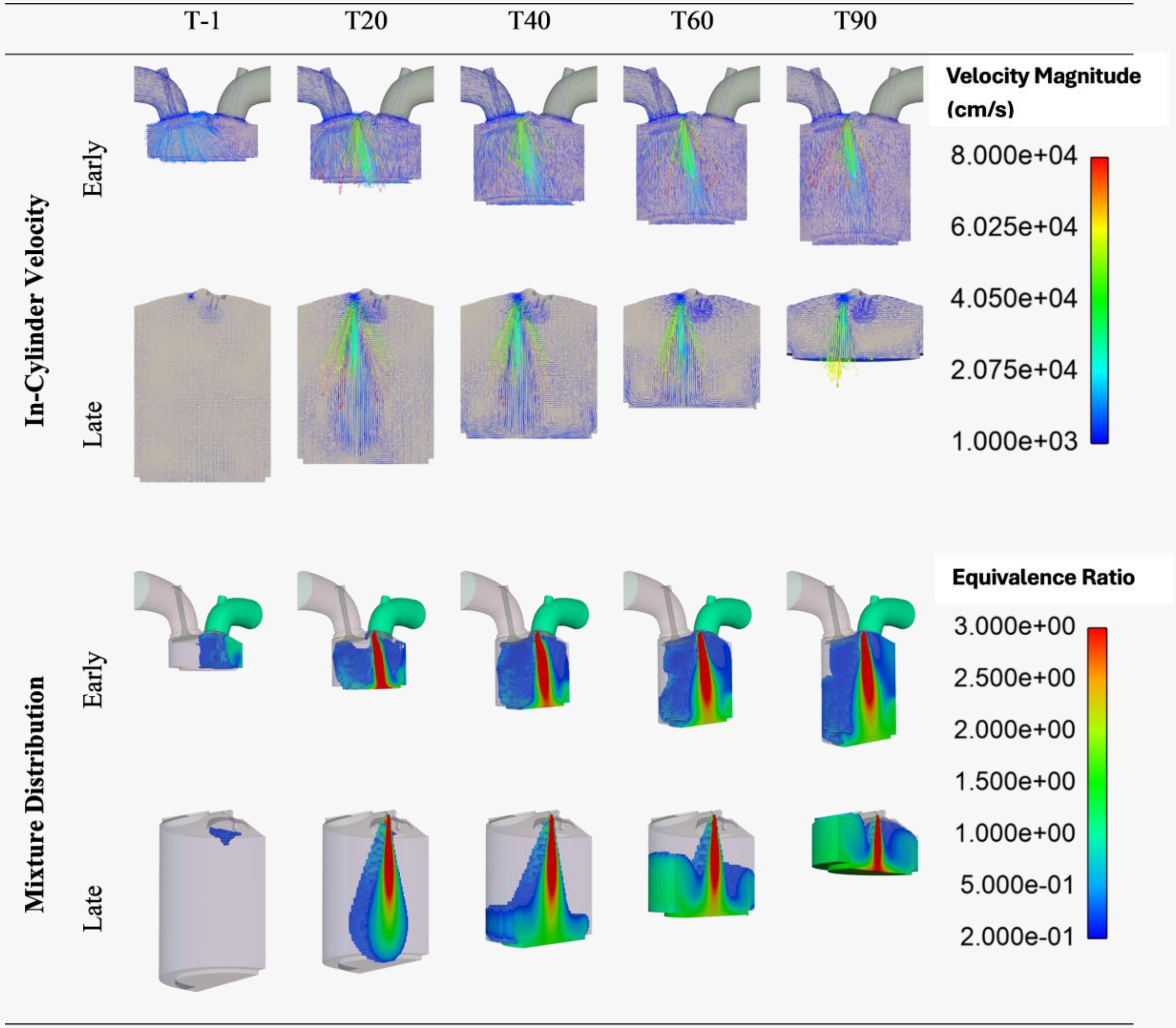


CNG

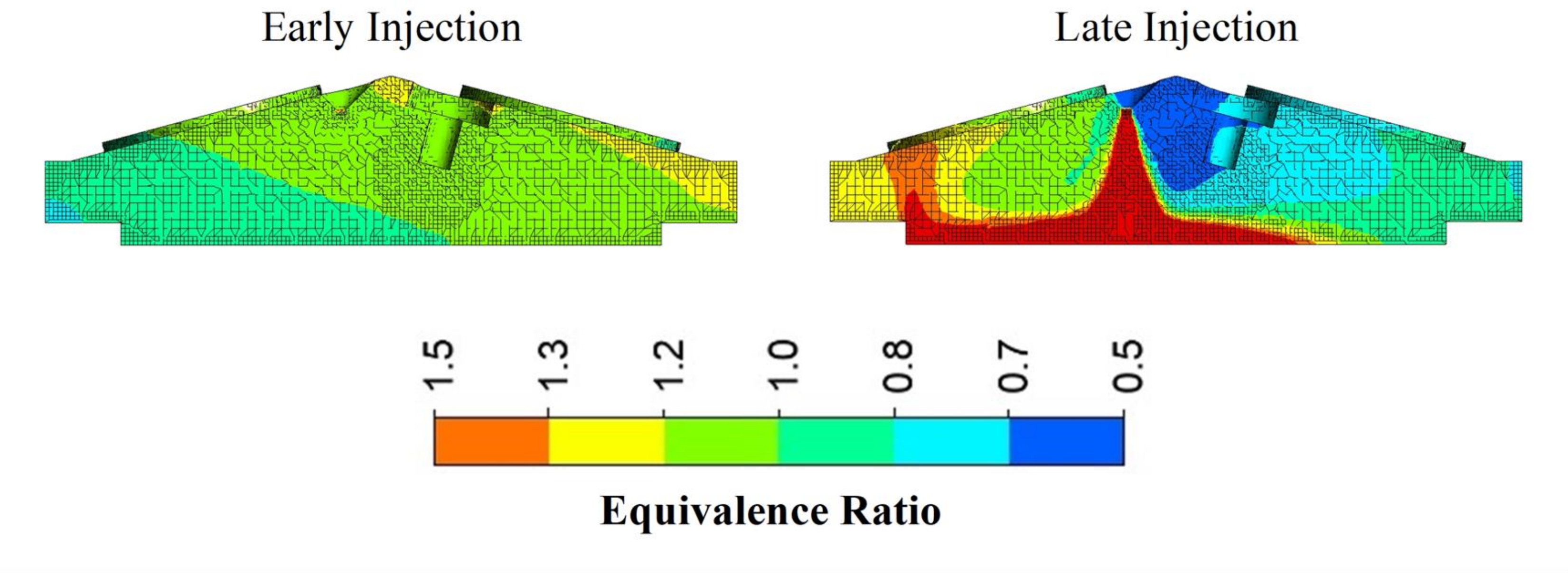


Gasoline

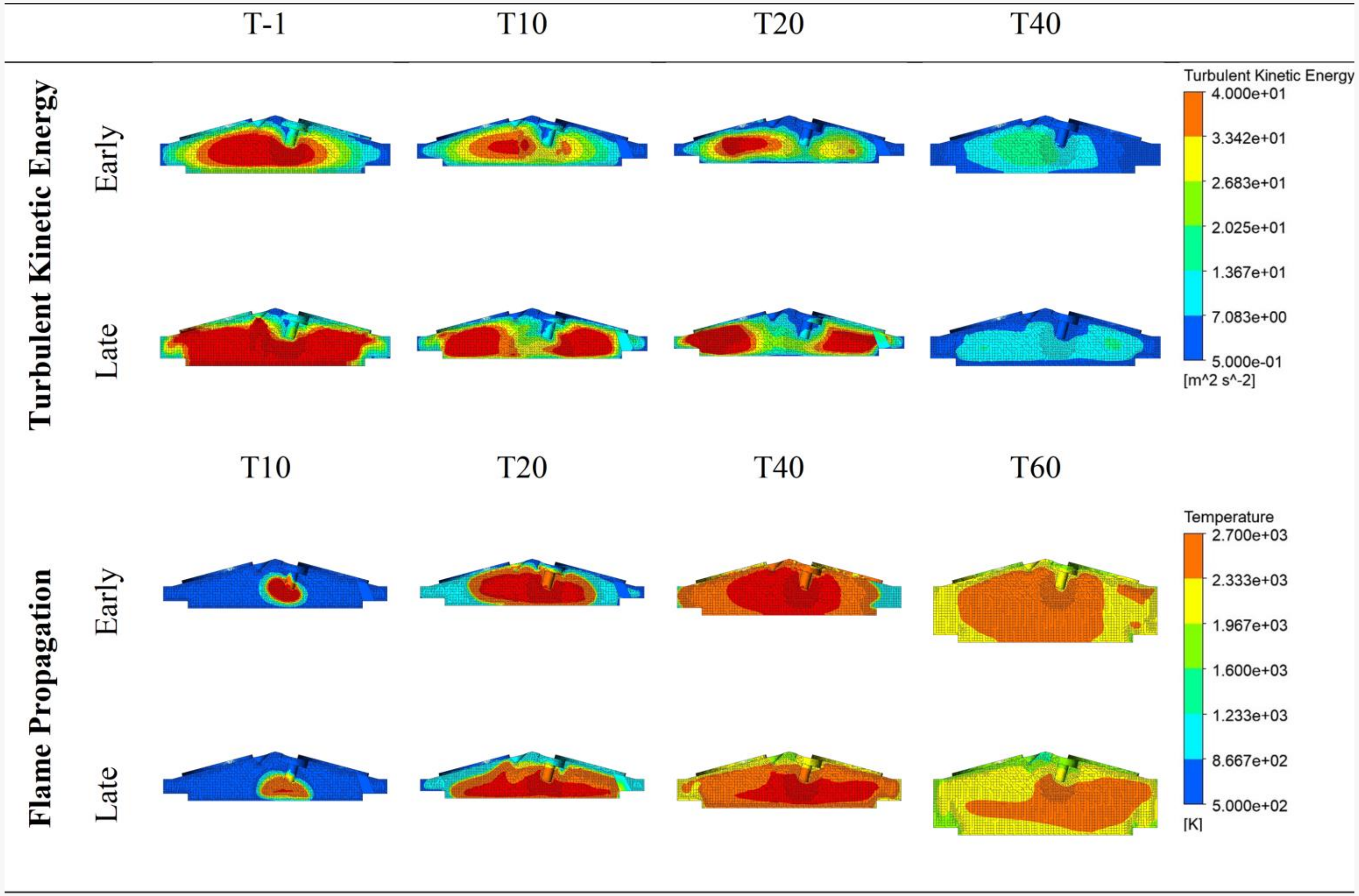
In-cylinder Flow: Fuel penetration and spray characteristics were significantly influenced by injection timing



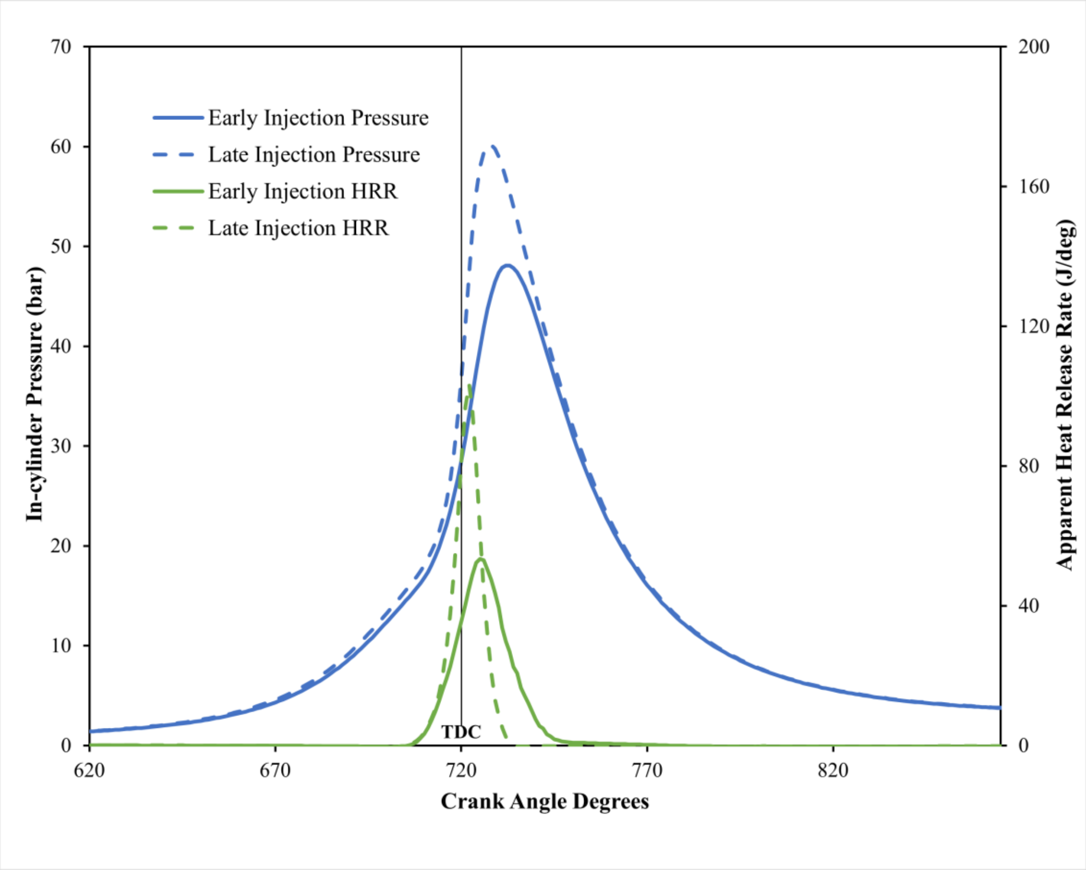
Mixture Distribution Prior to Ignition

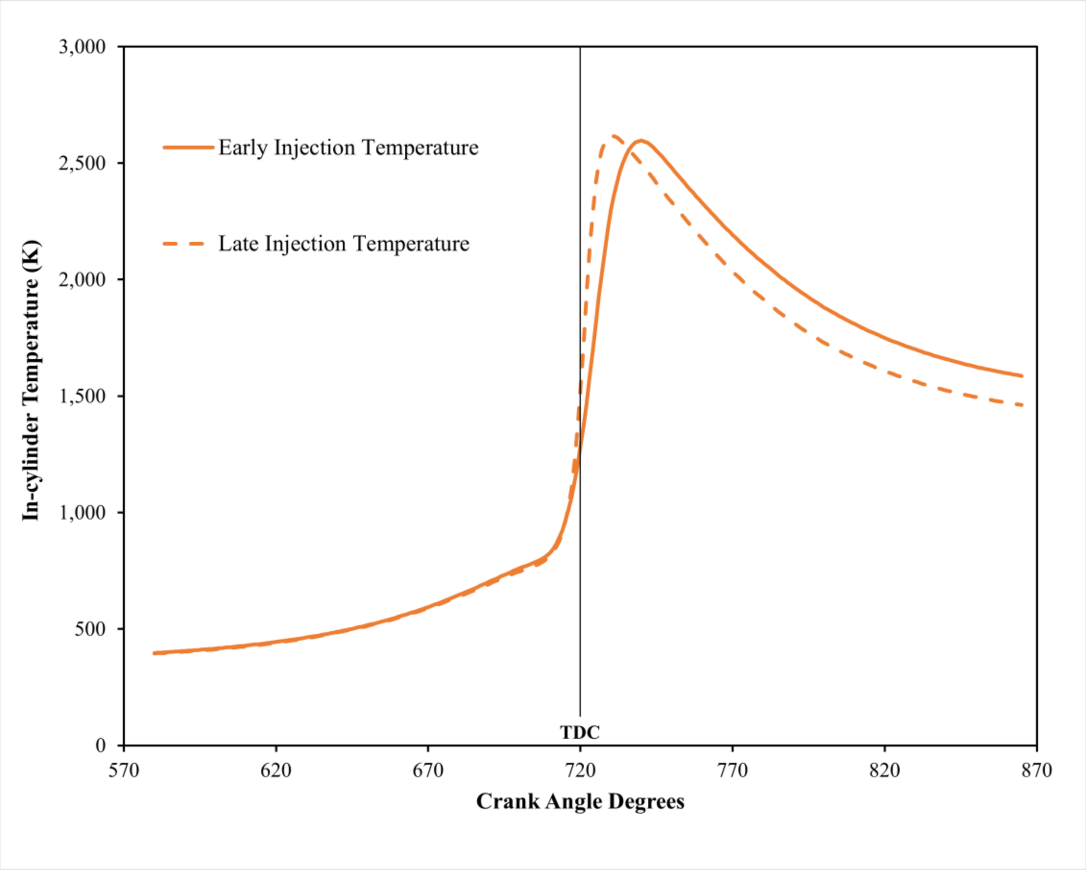


Combustion: There is a correlation between the flame propagation pattern and the preceding TKE field

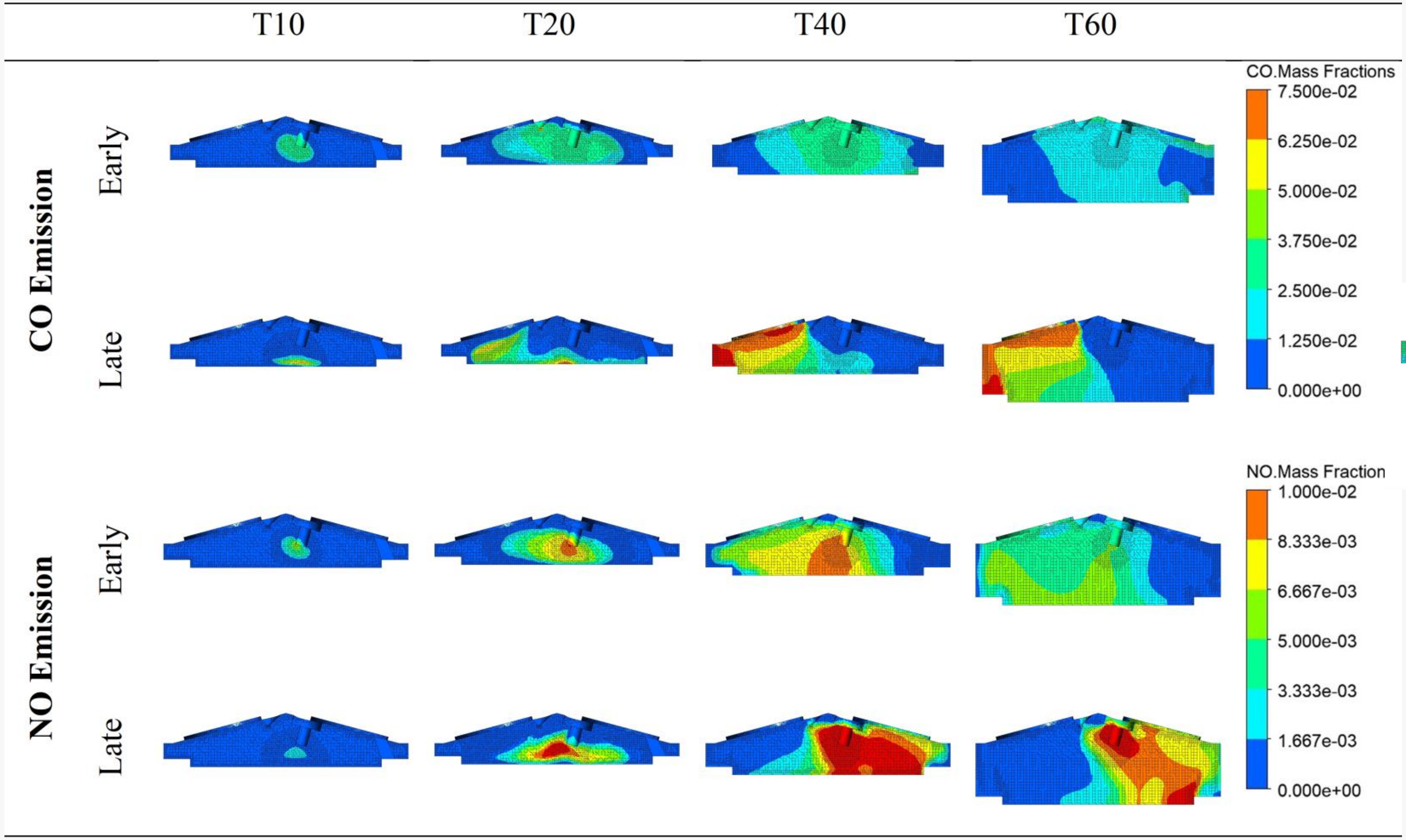


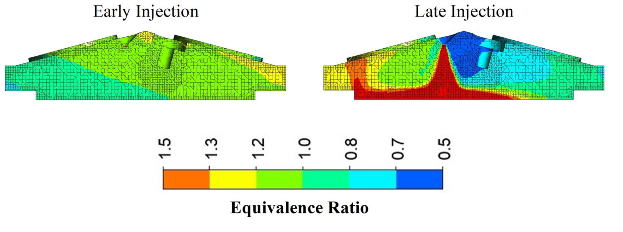
Combustion: Late injection increased the pressure and heat release build-up while shortening the combustion duration



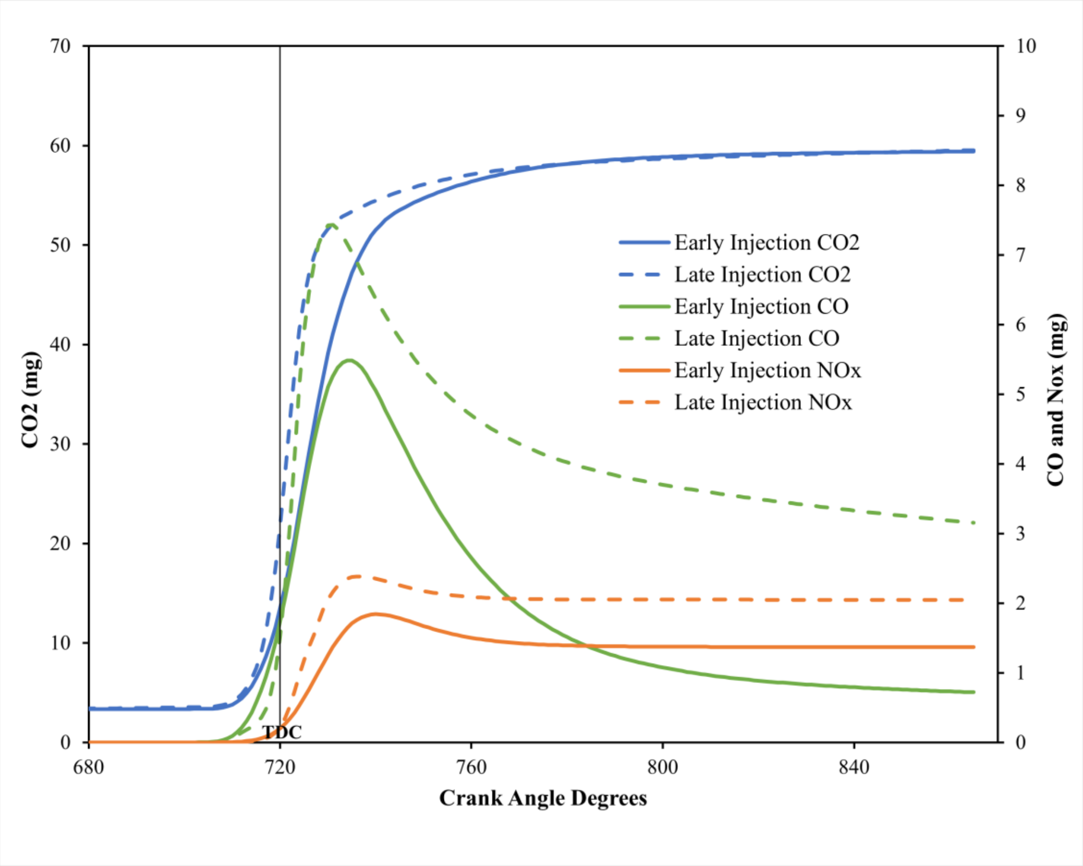


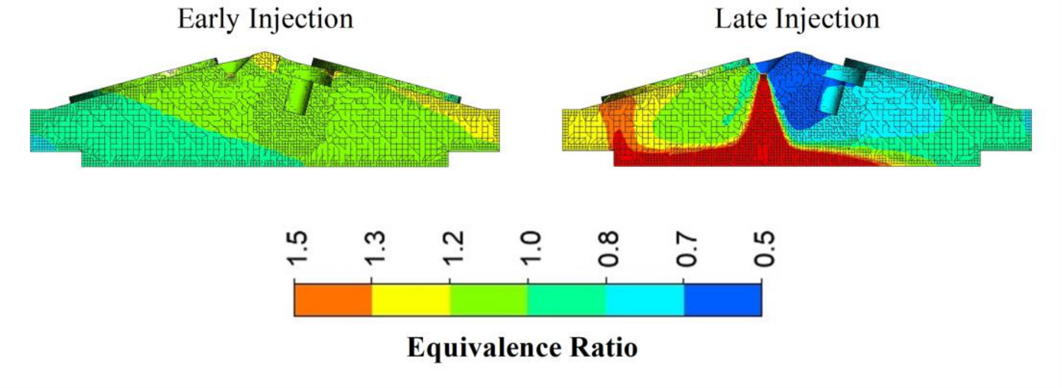
Emissions: Locally rich and lean fuel regions encouraged the formation of CO and NO$_x$ respectively



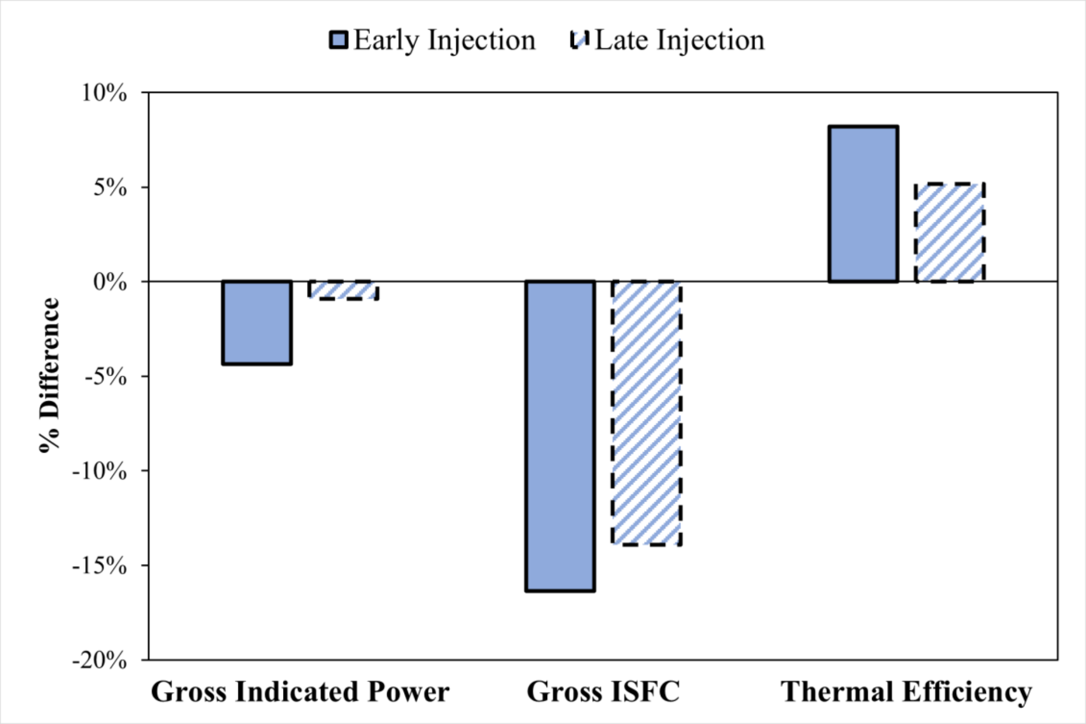


Emissions: Delaying injection increased NO$_x$ formation and CO emission due to poor homogeneity

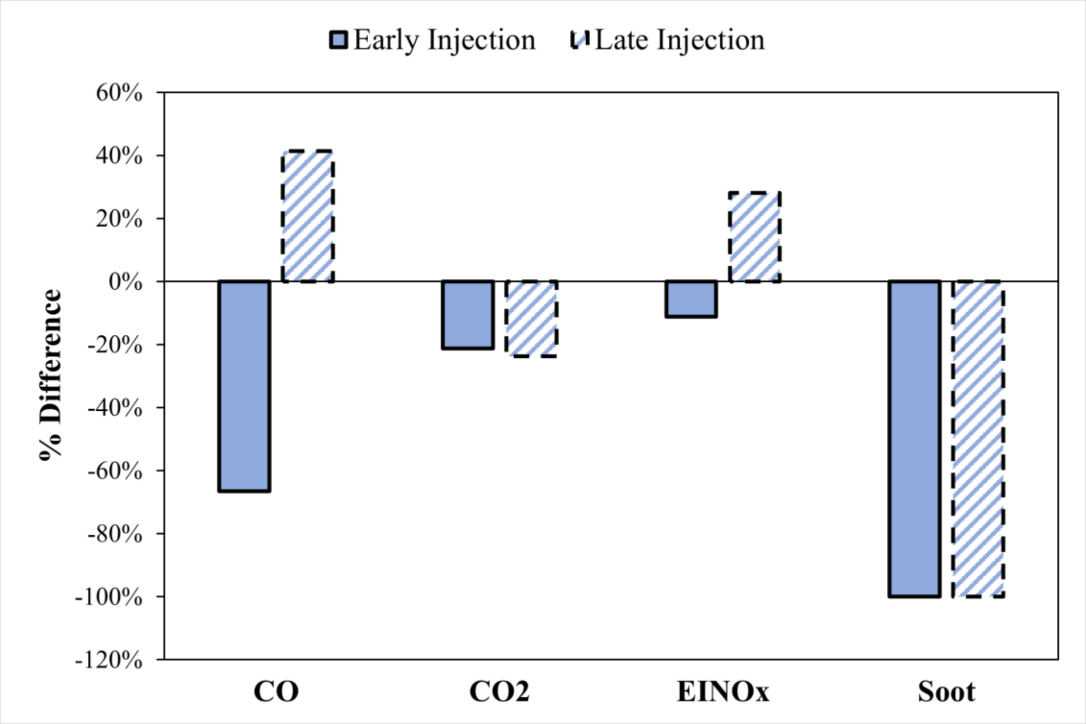




Summary: Late injection improved power output at the cost of increasing CO and NO_x emissions



Performance



Emissions

Conclusions

- Delaying injection till the compression stroke improved the combustion rate at the cost of increased CO and NO_x emissions
- Increased in-cylinder turbulence was primarily responsible for the influence of late injection on performance although poor mixture homogeneity compromised the ensuing combustion
- The study suggests that the injector orientation be adjusted, and the piston head be modified to produce a richer fuel mixture around the spark plug while ensuring sufficient mixing time prior to ignition
- Overall, CNG was predicted to reduce CO_2 emissions by 20-25%, decrease fuel consumption by approximately 15%, and improve the engine’s thermal efficiency by up to 8%.

Recommendations:

Possible areas for future studies include:

- Investigation of the effect of fuel composition on the combustion characteristics
- Exploration of hybridization as a means of emissions control

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Q&A

Thank you for listening!

Let's have your questions

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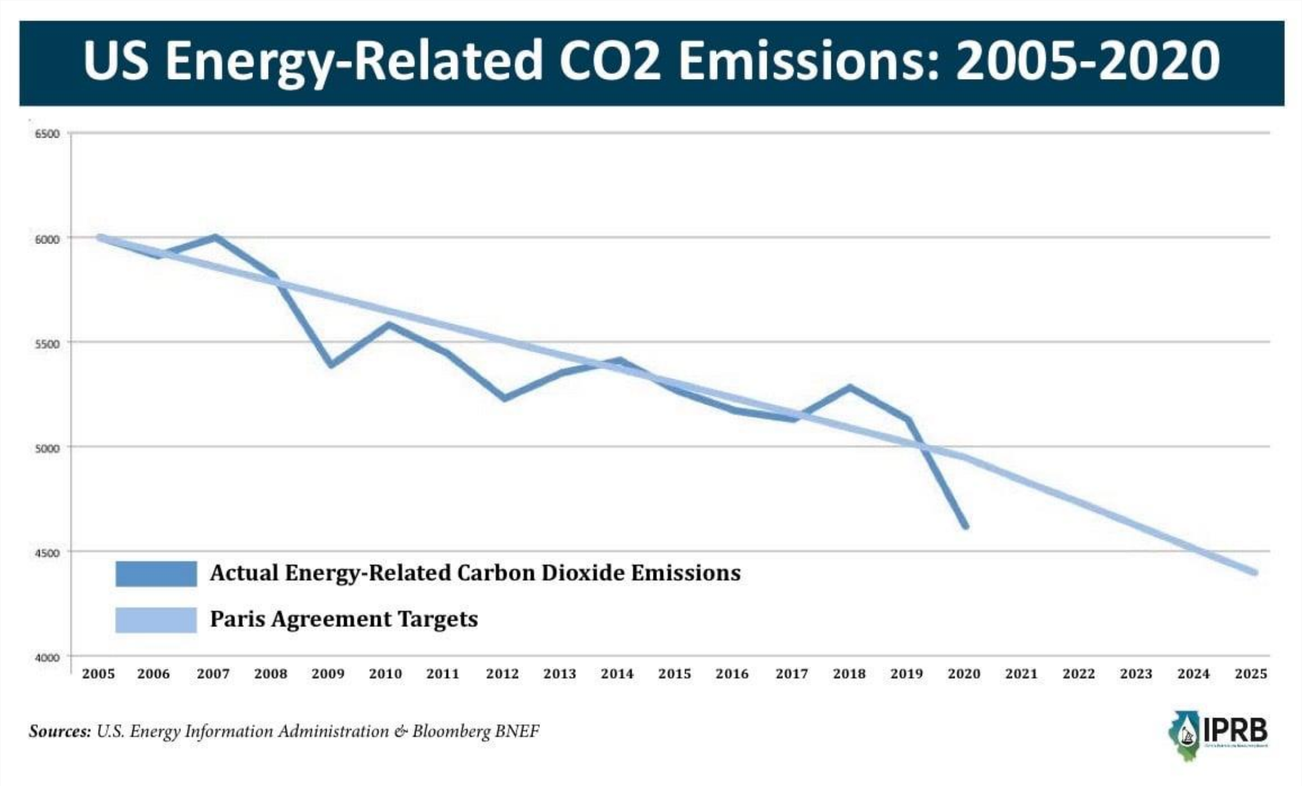
FOR LEARNING AND CULTURE

Impact of Switching to Natural Gas



US Energy-Related CO2 Emissions: 2005-2020

Sources: *U.S. Energy Information Administration & Bloomberg BNEF*