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

Abdulazeez B. Oni[1], Ayodele T. Oyeniran[2*], Bamiji Z. Adewole[3]; Samson K. Fasogbon[4], Abraham A. Asere[5]

[1,2,3] Department of Mechanical Engineering, Obafemi Awolowo University, Ile-Ife, Nigeria.

[4]Department of Mechanical Engineering, University of Ibadan, Ibadan, Nigeria.

[5]Department of Automotive Engineering, Elizade University, Ilara Mokin, Nigeria

* Corresponding author atoyeniran@oauife.edu.ng; oyeniranat@yahoo.com

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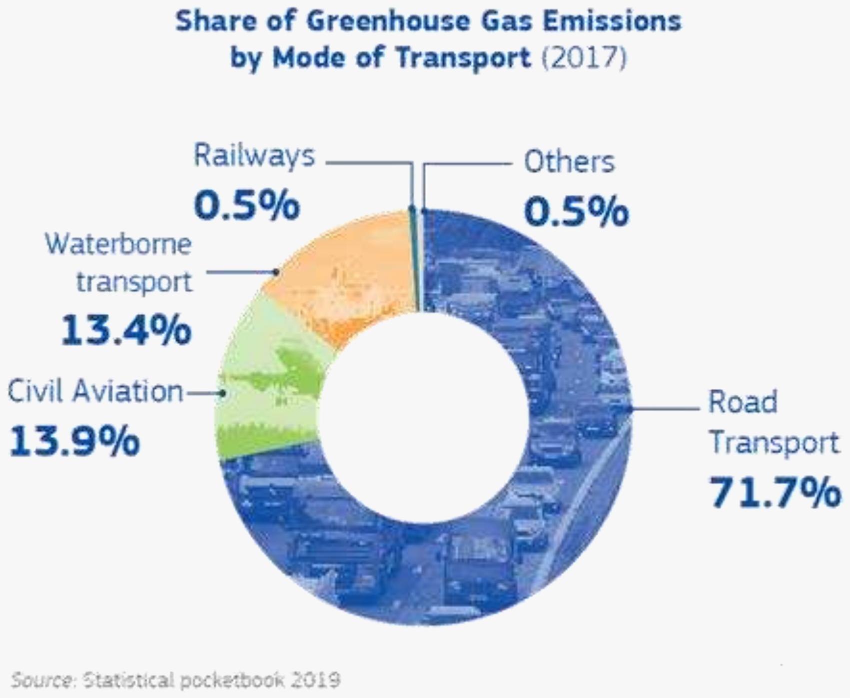
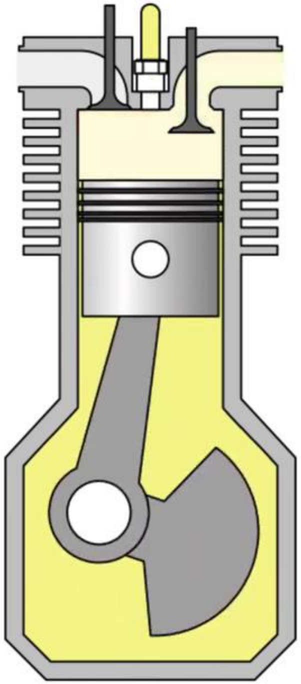
The Promise of Natural Gas

- 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
- Natural gas can provide an immediate reduction in emissions. It is cheap and abundantly available in Nigeria



Primer: Fuel Combustion



Current Understanding and Challenges

- Natural Gas is widely used in its compressed form (CNG)
  - Limitations:
    - CNG has a low flame speed, and it requires a high ignition energy using a spark (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:
    - Direct injection of CNG improves the volumetric efficiency, and power (Tuner, 2016)
    - Increasing the compression ratio gives a fast-burning rate (Huang et al., 2008)
- Outstanding Challenges
  - The combustion characteristics of CNG depend on its composition which varies significantly by geographical location (Chala et al., 2018)
  - The injection timing significantly affects the performance of CNG engines (Aljamali et al., 2016) ~optimal timing?

Statement of Research Problem

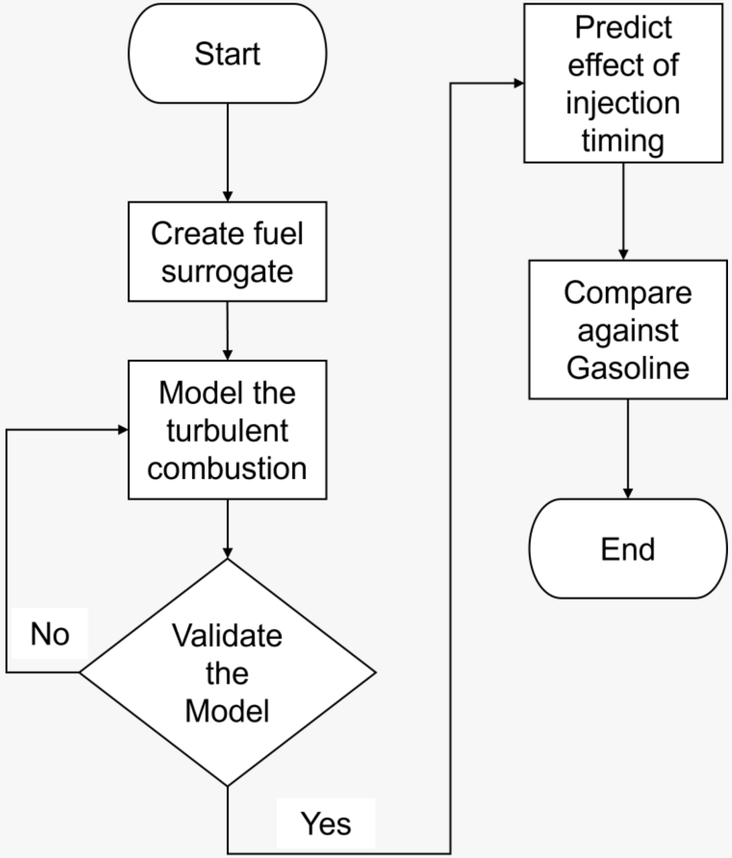
- To address this challenges, it is essential to investigate the effects of injection timing on the combustion of Nigerian compressed natural gas in Spark Ignition Direct Injection (SIDI) engines

Specific Objectives

The objectives of this study are to:

1. Investigate the effect of early and late injections on the combustion behaviour and emissions from the engine
2. Evaluate the comparative performance of Nigerian CNG and gasoline in the engine.

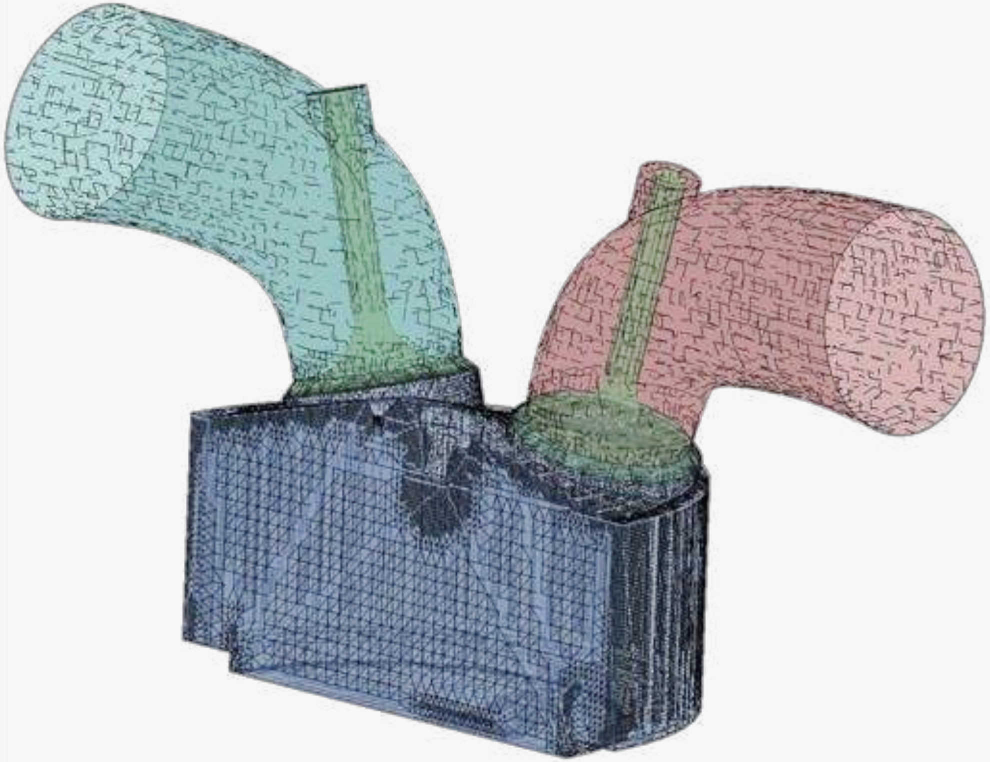
Methodology: Overview



Molar composition of natural gas from the Utorogu gas plant, Nigeria (Sonibare and Akeredolu, 2004)

Specie	%
Methane	90.12
Ethane	6.94
Propane	2.09
N-butane	0.361
I-butane	0.414
N-pentane	0.005
I-pentane	0.007

Model Geometry



0.5 L AVL Single Cylinder Engine Specifications

Parameters	**Value**
Bore	8.2 cm
Stroke	9 cm
Connecting rod length	14.75 cm
Compression ratio	10.5:1
Number of valves	4

Governing Equations

MASS

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

SPECIES

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

MOMENTUM

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

ENERGY

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

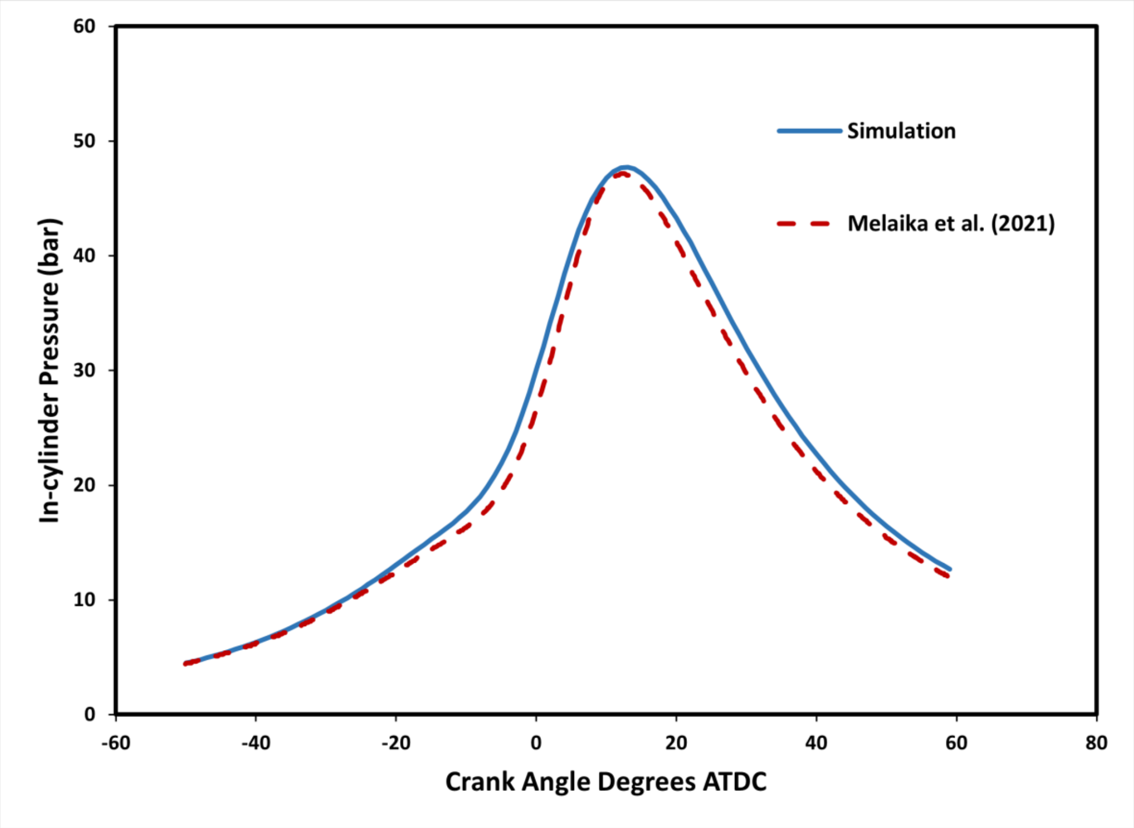
Spray source terms

Combustion source terms

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

Validation



In-cylinder Pressure (bar)
60
50
40
30
20
10
0
-60
-40
-20
0
20
40
60
80
Crank Angle Degrees ATDC
Simulation
Melaika et al. (2021)

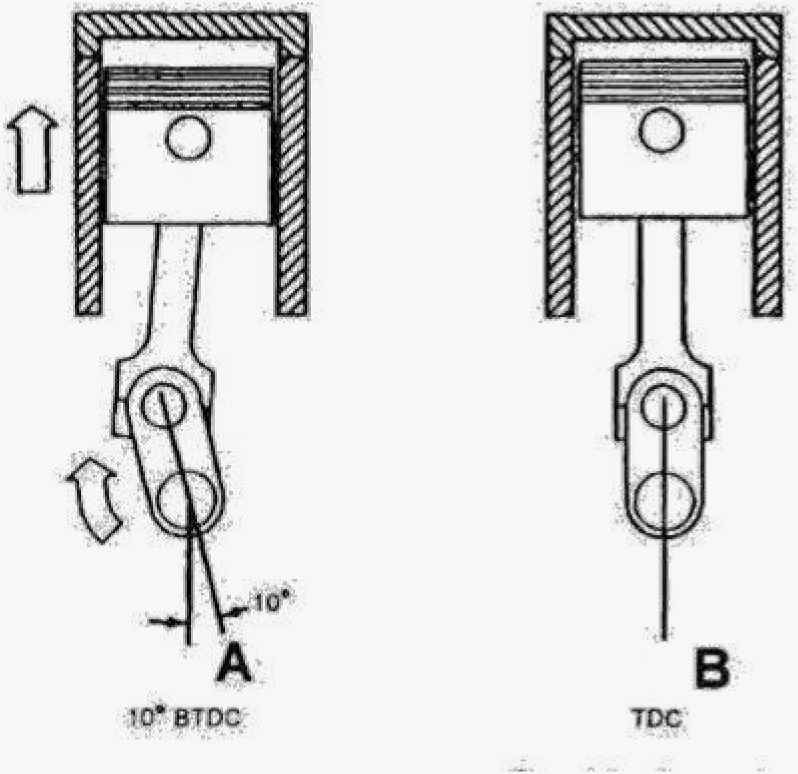
Objective 1

The objectives of this study are to:

1. Investigate the effect of early and late injections on the combustion behaviour and emissions from the engine
2. Evaluate the comparative performance of Nigerian CNG and gasoline in the engine.

Methodology: Objective 1

- Effect of early and late injection timing was investigated at a constant injection pressure of 50 bar on an engine running at 1500 rpm and wide open throttle
- Injection at 310° and 135° (BTDC) were used to simulate early and late injection respectively.



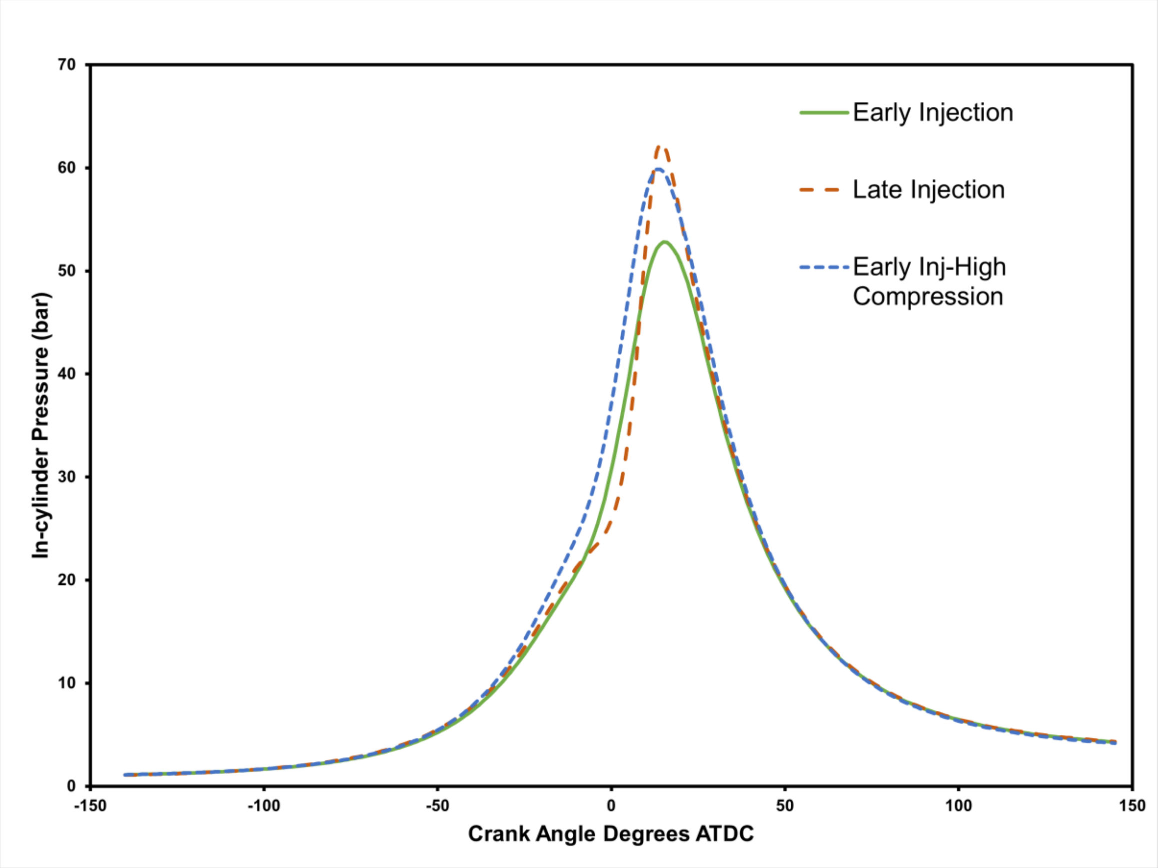
Source: www.constructionmanuals.tpub.com

Methodology: Objective 1

3-D turbulent combustion of CNG was simulated using the CFD software (Ansys Forte)

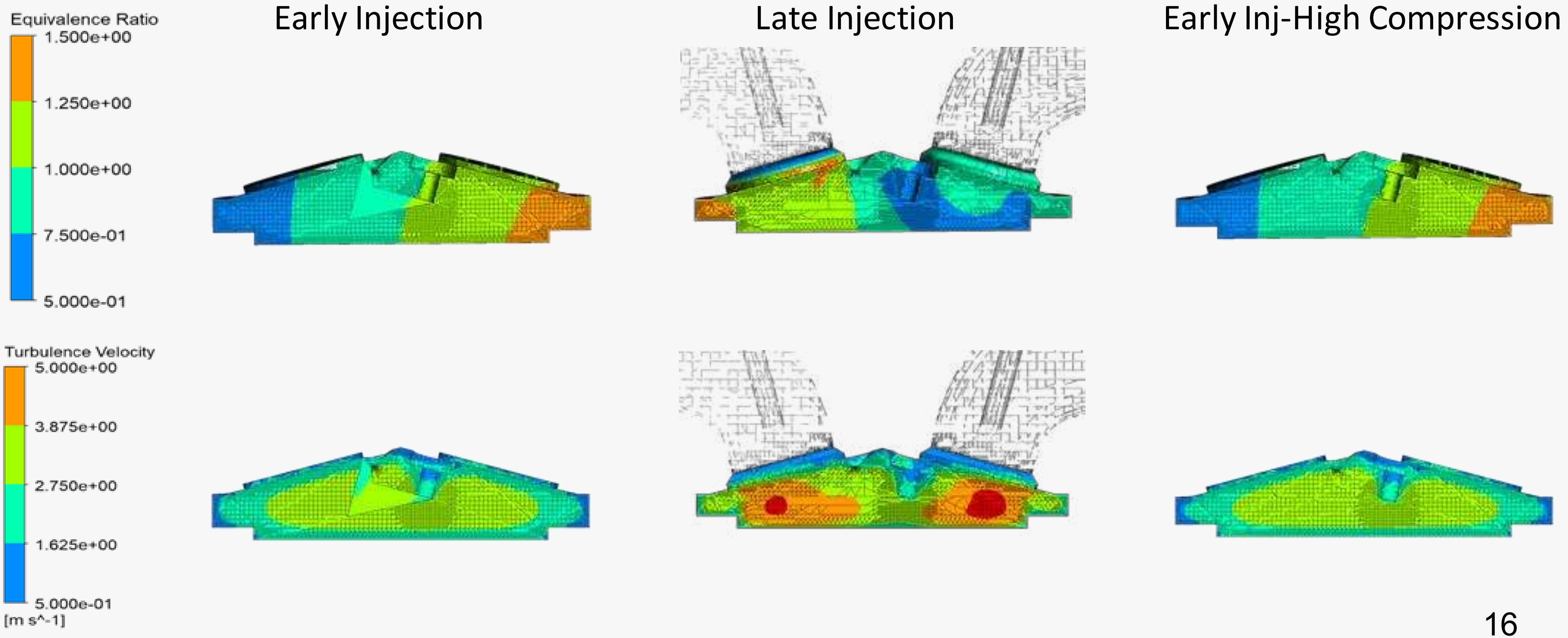
- Analysis 1: Combustion
  - The in-cylinder pressure, temperature, and heat release curves were obtained from the CFD code
- Analysis 2: Emissions
  - Cycle averaged emission levels of CO, CO2, NO, and NO2 were obtained from the coupled chemical kinetics software (Chemkin-Pro)

Combustion: Late injection improves flame speed



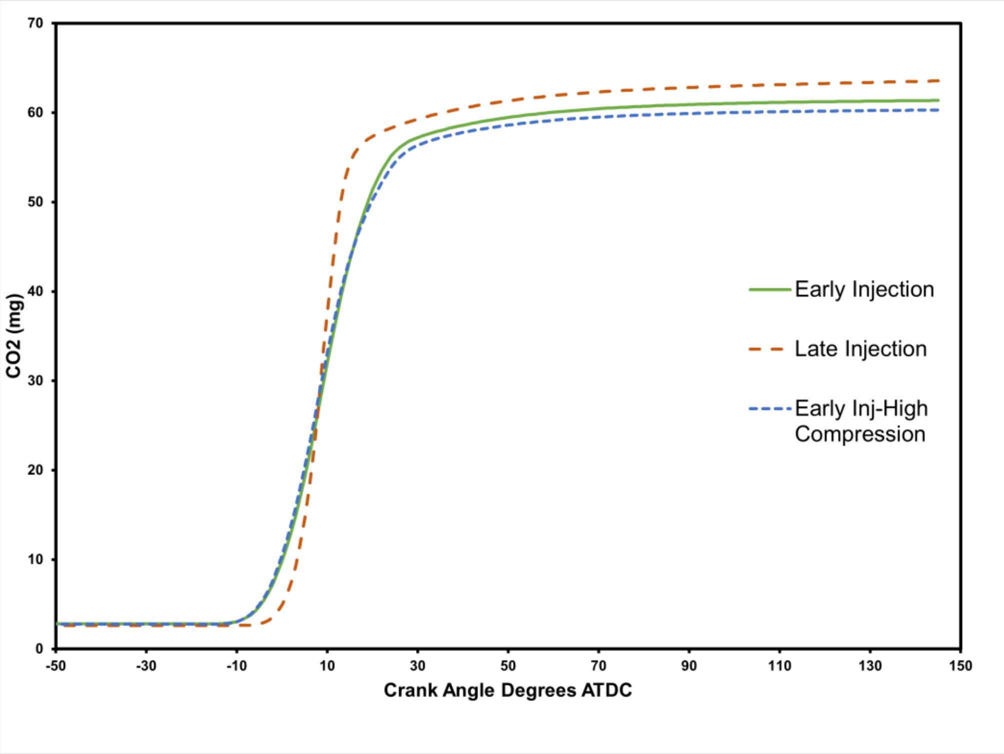
The result suggests:
Injecting CNG during the compression stroke (i.e. late), improves its burning rate and the resultant pressure build up.

Combustion: CNG flame propagation may be influenced by In-cylinder turbulence

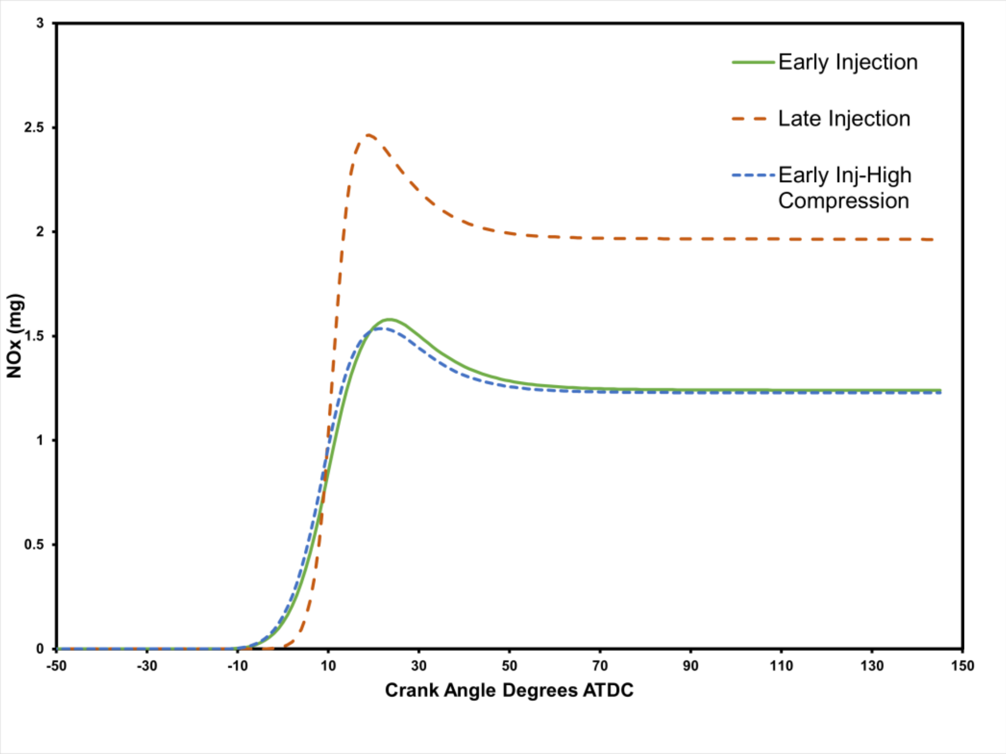


Emissions: Poor mixture formation from late injection increases emissions

CO2



NOx



Objective 2

The objectives of this study are to:

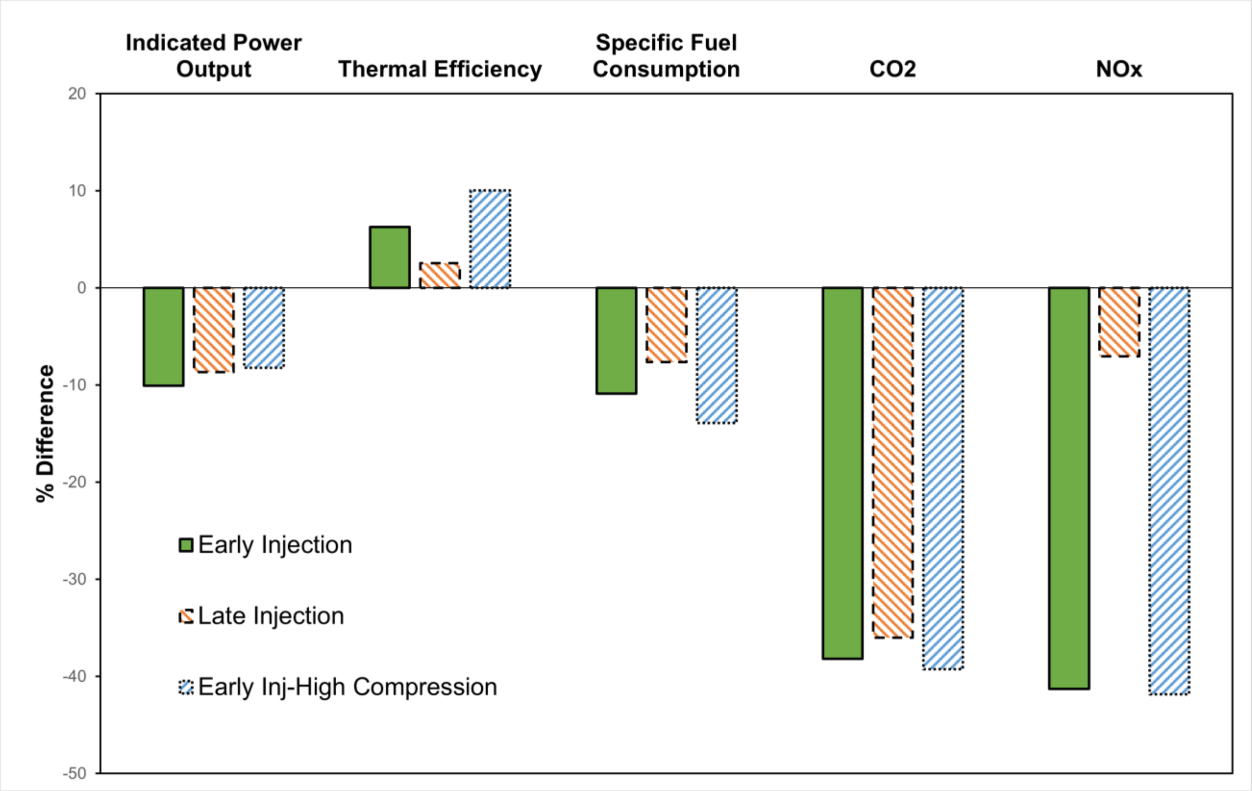
1. Investigate the effect of early and late injections on the combustion behaviour and emissions from the engine
2. Evaluate the comparative performance of Nigerian CNG and gasoline in the engine.

Methodology: Objective 2

- The combustion of CNG and gasoline (E10) were simulated at stoichiometric air-fuel ratios under similar operating conditions

- The following metrics were computed from the results obtained
  - Engine thermal efficiency
  - Indicated specific fuel consumption
  - CO, CO2, NO, NO2 and Soot emissions per cycle

Performance: CNG increased thermal efficiency, reduced fuel consumption and emissions



Difference of CNG over Gasoline (E10)

Conclusion

- We conclude that:
  - Nigerian CNG in SIDI engines burns efficiently and offers significantly reduced CO_2 and NO_x emissions.
  - Delaying gas injection till the compression stroke significantly improves the rate of combustion but, it does so at the expense of increased emissions, particularly NO_x
  - Combining a early injection strategy with an increased compression ratio up to 12:1 could offer similar performance benefits without an emissions penalty.

Recommendations

- We recommend that:
    - Conventional vehicles should be converted to use CNG as it is more efficient and performs comparably to gasoline
- Possible areas for future studies include:
    - Investigation of the combustion characteristics of CNG obtained from other gas plants in Nigeria, and the development of a “Standard”
    - Exploration of hybridization as a means of emissions control

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Q&A

Thank you for listening!

Let's have your questions

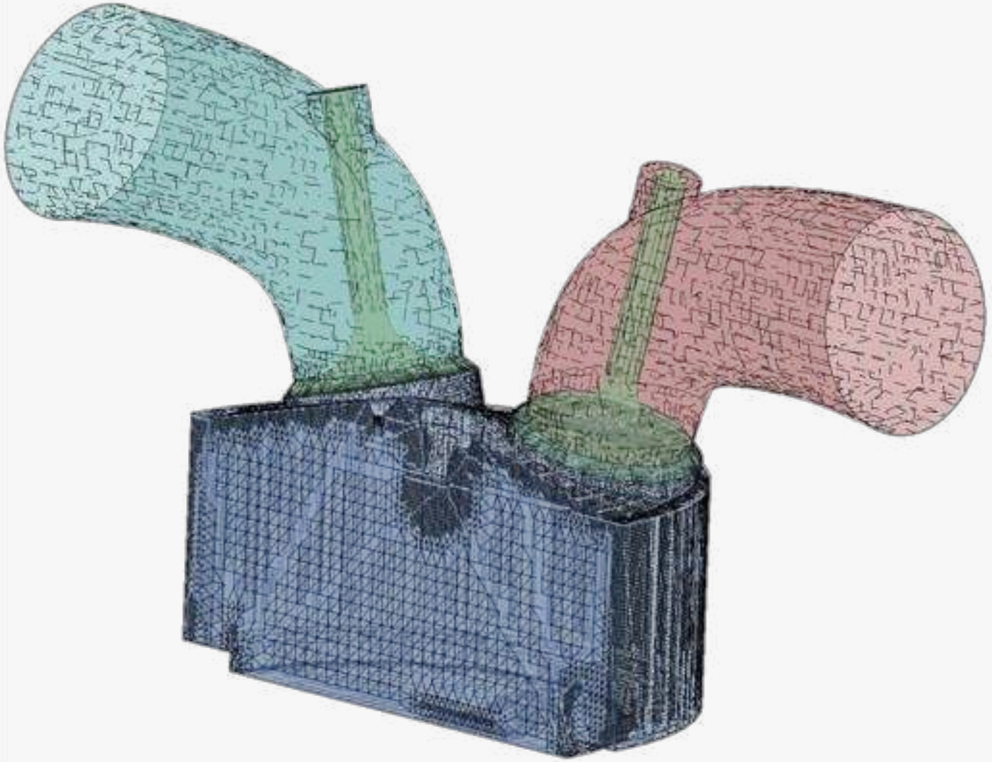
www.linkedin.com/in/abdulazeez-oni

azeez_oni@outlook.com

Q&A

Region/Variable	Refinement Type	Size Fraction	Cell Layers	Active
Open	Surface	$^{1}/_{2}$	2	Always
Walls	Surface	$^{1}/_{2}$	1	Always
Valves	Surface	$^{1}/_{4}$	2	Always
Spark	Point	$^{1}/_{8}$	N/A	Always
TDC	Surface	$^{1}/_{8}$	2	680 – 740 CA
Temperature	AMR	$^{1}/_{8}$	N/A	700 – 800 CA
Velocity	AMR	$^{1}/_{4}$	N/A	Always
Fuel vapor mass fraction	AMR	$^{1}/_{8}$	N/A	410 – 540 CA
G	AMR	$^{1}/_{8}$	N/A	702 – 762 CA

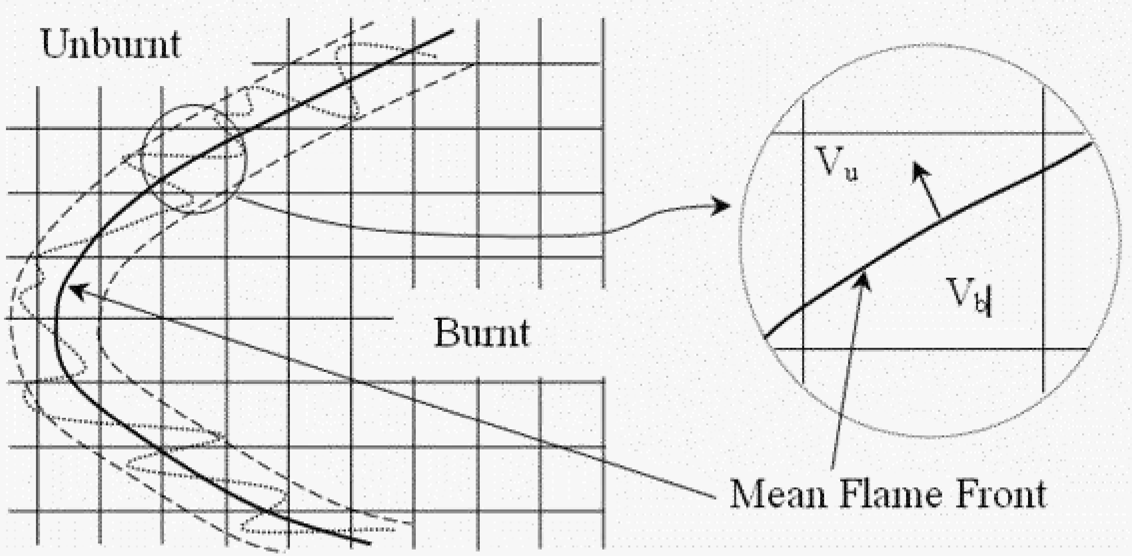
Q&A



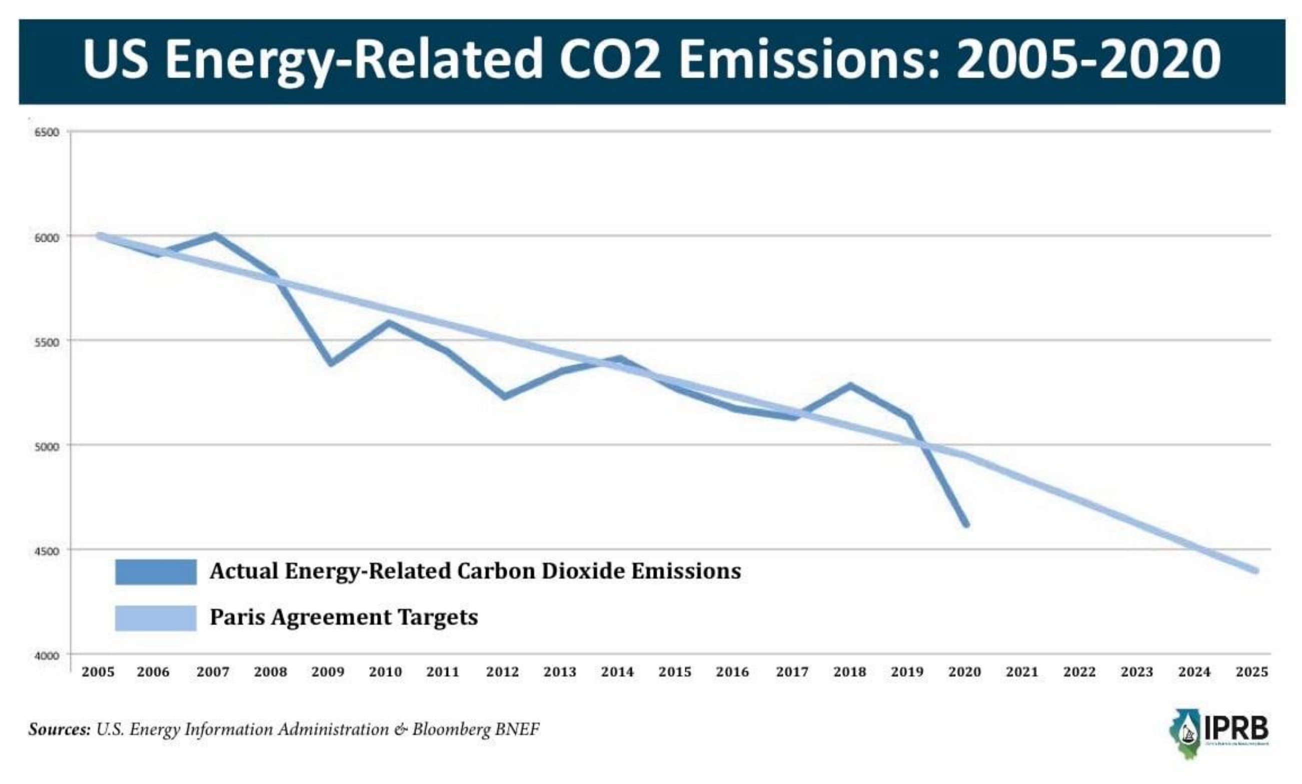
Q&A

$$\frac{\partial \tilde{G}}{\partial t} + \left(\tilde{\vec{u}} - \vec{u}_{vertex}\right) \cdot \nabla \tilde{G} = \frac{\bar{\rho}_u}{\bar{\rho}_b} S_T^0 \left|\nabla \tilde{G}\right| - D_T \tilde{\kappa} \left|\nabla \tilde{G}\right|,$$

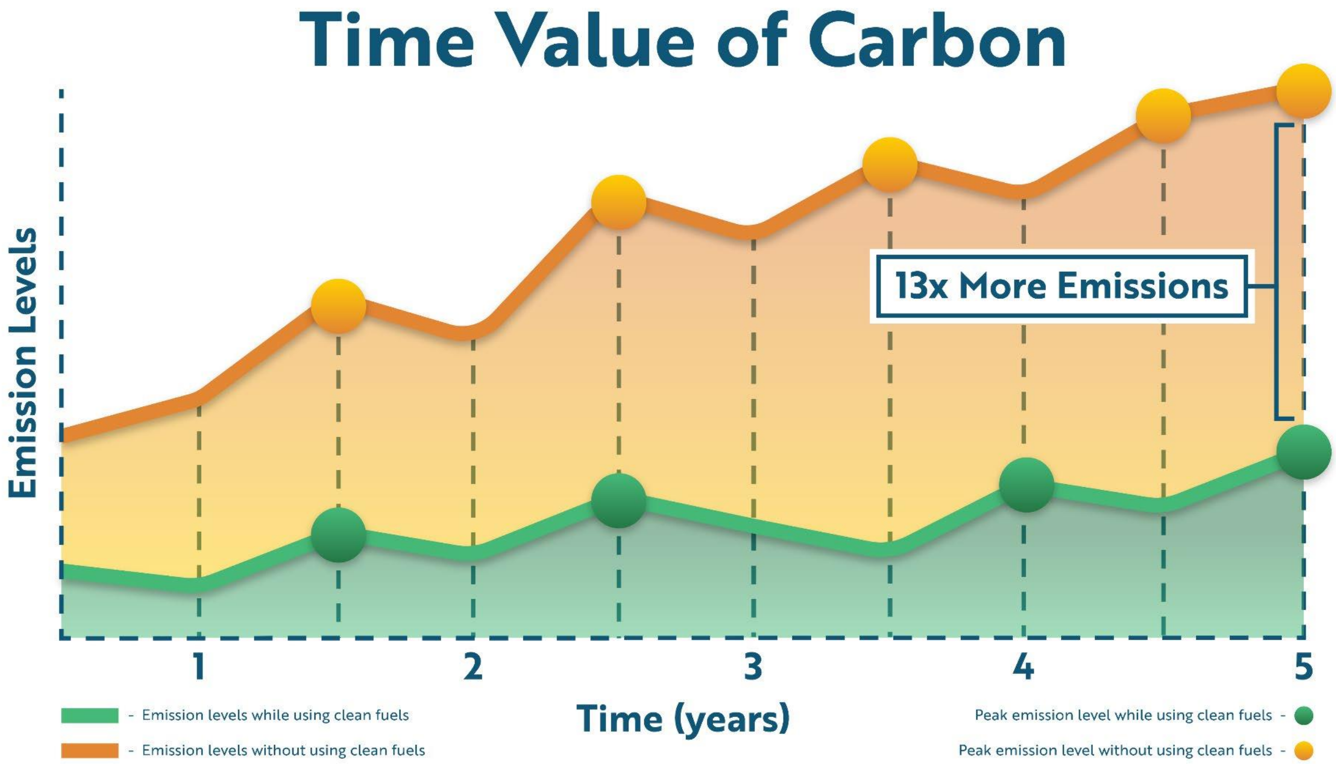
$$\frac{\partial \widetilde{G''^2}}{\partial t} + \tilde{\vec{u}} \cdot \nabla \widetilde{G''^2} = \nabla_{|} \cdot \left(\frac{\bar{\rho}_u}{\bar{\rho}_b} D_T \nabla_{|} \widetilde{G''^2}\right) + 2 D_T \left(\nabla \tilde{G}\right)^2 - c_s \frac{\tilde{\varepsilon}}{\tilde{k}} \widetilde{G''^2}$$



Q&A


US Energy-Related CO2 Emissions: 2005-2020
6500
6000
5500
5000
4500
4000
Actual Energy-Related Carbon Dioxide Emissions
Paris Agreement Targets
2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025
Sources: U.S. Energy Information Administration & Bloomberg BNEF
IPRB

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