High-Efficiency Mixing Controlled Compression Ignition Combustion of Propane Dimethyl Ether (DME) Blends

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June 22, 2022

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Award Number: DE-EE0009879

Project ID #: ACE181

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Overview

Timeline

- Start: April 2022
- End: March 2025
- Completion 0%

Budget

- Total project funding $2.97M
- DOE: $2.37M
- Cost share: $0.60M

Partners

- Wisconsin Engine Research Consultants
- WM International
- University of Central Florida
- Propane Education and Research Council
- Oberon Fuels

Barriers

- Propane fueled engines offer the potential to reduce GHG emissions due to the lower carbon content of the fuel, but medium and heavy-duty engines typically are not well-suited for spark-ignition operation → development of a mixing controlled compression ignition (MCCI) combustion process utilizing propane is needed
- Conventional fuel systems are not well-suited for use with propane or propane / di-methyl ether blends at high injection pressures required for mixing controlled combustion → development of a high pressure propane/DME fuel system is needed.

Relevance

Relevance

- Medium-duty greenhouse gas (GHG) emission standards will require a 10% reduction by 2027, requiring substantial changes in technology to significantly increase engine efficiency. Utilizing propane and DME in these applications has the potential to substantially reduce the GHG or CO_2 emissions compared to typical diesel operation due to the lower carbon content of the fuel.
- The current state-of-the-art LPG engine has CO_2 emissions of 551 g/bhp-hr and NOx emissions of 0.02 g/bhp-hr over the FTP cycle (cycle average BTE = 31.5%). A comparable diesel engine has a BTE of 37.1% over the same cycle → achieving the efficiency of a diesel engine with a propane fueled engine would result in CO_2 emissions of 468 g/bhp-hr, a 15% reduction in the engine out CO_2 emissions.
- Using renewable DME enables further reductions in $BSCO_2$ emissions due to well-to-tank CO_2 reductions
- Enabling use of propane and propane/DME blends with diesel-like efficiency has the potential for real-world achievable reductions in $BSCO_2$

Objective of Budget Period 1

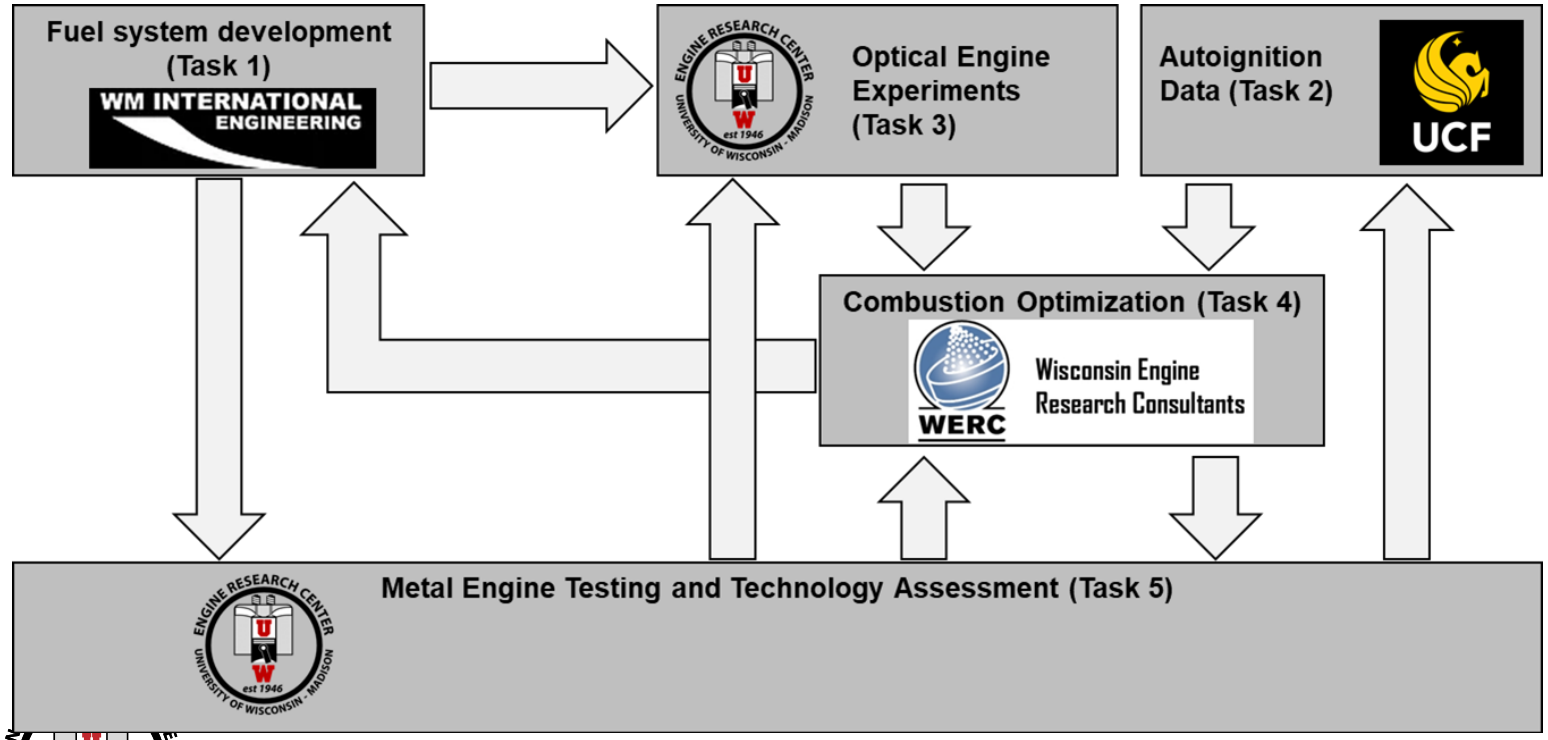
- Demonstrate compression ignition operation of propane in a medium-duty engine to identify the required operating parameters and supply data for computational model validation.

Full Program Objective

- The overall goal of this project is to enable a 15% reduction in CO_2 emissions compared to current diesel engines by developing a mixing controlled compression ignition combustion strategy capable of operating on blends of propane and DME.

Approach

- Couple engine modeling, injector developments, and engine experiments to develop a combustion strategy capable of achieving mixing controlled combustion of propane and propane/DME blends to provide insight into needed hardware modifications and potential benefits and challenges.
- Provide fundamental engine and shock tube data suitable for propane and propane/DME blends at engine relevant conditions.



Program Goals

1) Development and assessment of a fuel system suitable for propane and propane/DME blends;
2) Computational led optimization of the combustion system capable of achieving stable, robust combustion over a range of propane and DME blends;
3) Engine-level experiments to demonstrate engine efficiency and emissions of the optimized hardware configuration;
4) Quantification of overall system performance, benefits, and drawbacks through comparisons with existing combustion systems. System-level comparison to existing combustion modes using cycle simulation tools.

Approach

Fuel system development (Task 1)

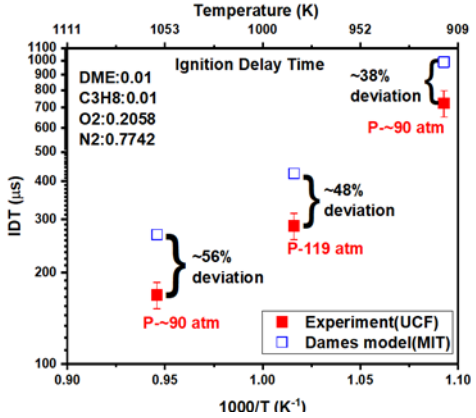
Objective: Develop a fuel system suitable for propane/DME mixtures at injection pressures above 1500 bar with multi-shot capability

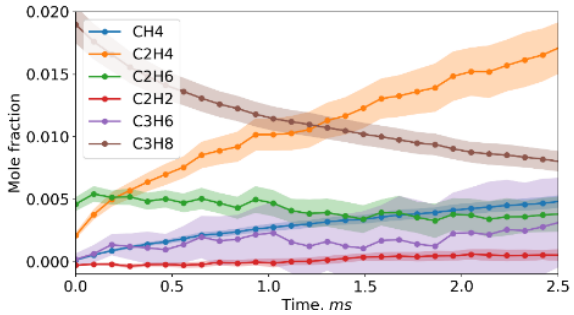
Approach: Adapt and modify WMI's DME fuel injection hardware to operate on propane/DME blends (optimized components to avoid cavitation and enable close coupled injections)

Propane/DME Autoignition delay Times and Speciation Measurements, Chemical Kinetics Model Development (Task 2)

Objective: Collect ignition data for propane/DME blends at MCCI engine relevant pressures and develop an improved chemical kinetics model

Approach: Perform high-pressure shock tube experiments at MCCI relevant conditions and develop improved models for use in CFD-based optimization

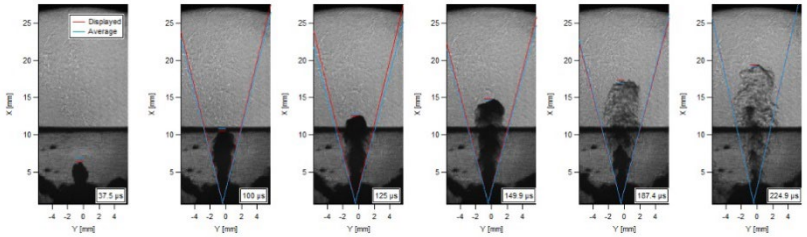




Optical Engine Experiments (Task 3)

Objective: Collect optical engine data to validate spray, mixing, and combustion models and provide fundamental insight into differences between propane MCCI and diesel fueled MCCI

Approach: Install high pressure propane/DME fuel system in an optically accessible engine and collect high speed imaging of spray, mixing, and combustion

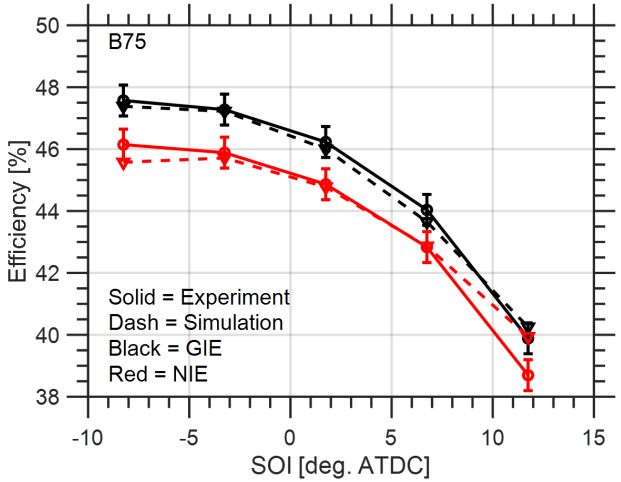


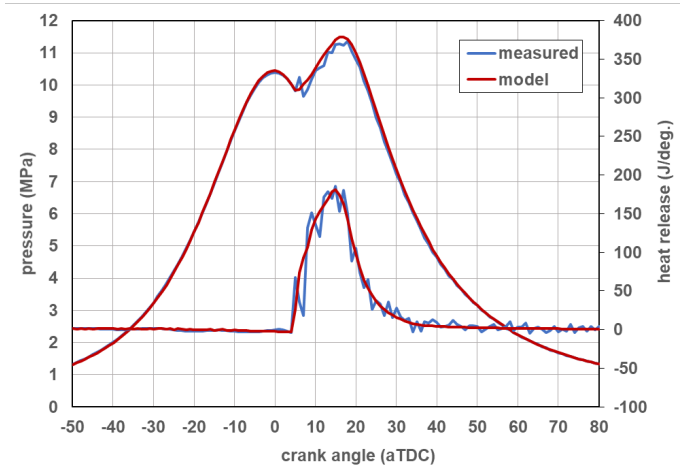
Approach

Combustion Optimization (Task 4)

Objective: Use validated CFD simulations to optimize the combustion chamber and injector configuration to enable robust propane MCCI combustion.

Approach: Validate model using shock tube data (chemistry), optical engine data (spray, mixing, and combustion), and metal engine data (performance and emissions) and perform design of experiments based optimization to select hardware needed for robust ignition of propane and propane/DME blends

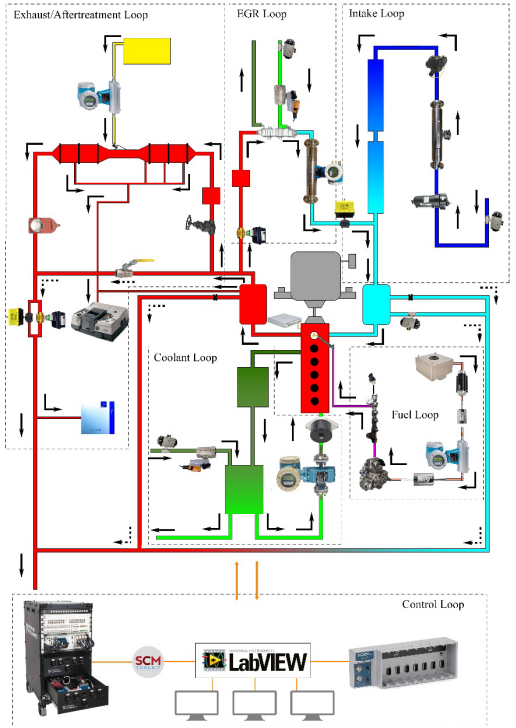




Metal Engine Testing (Task 5)

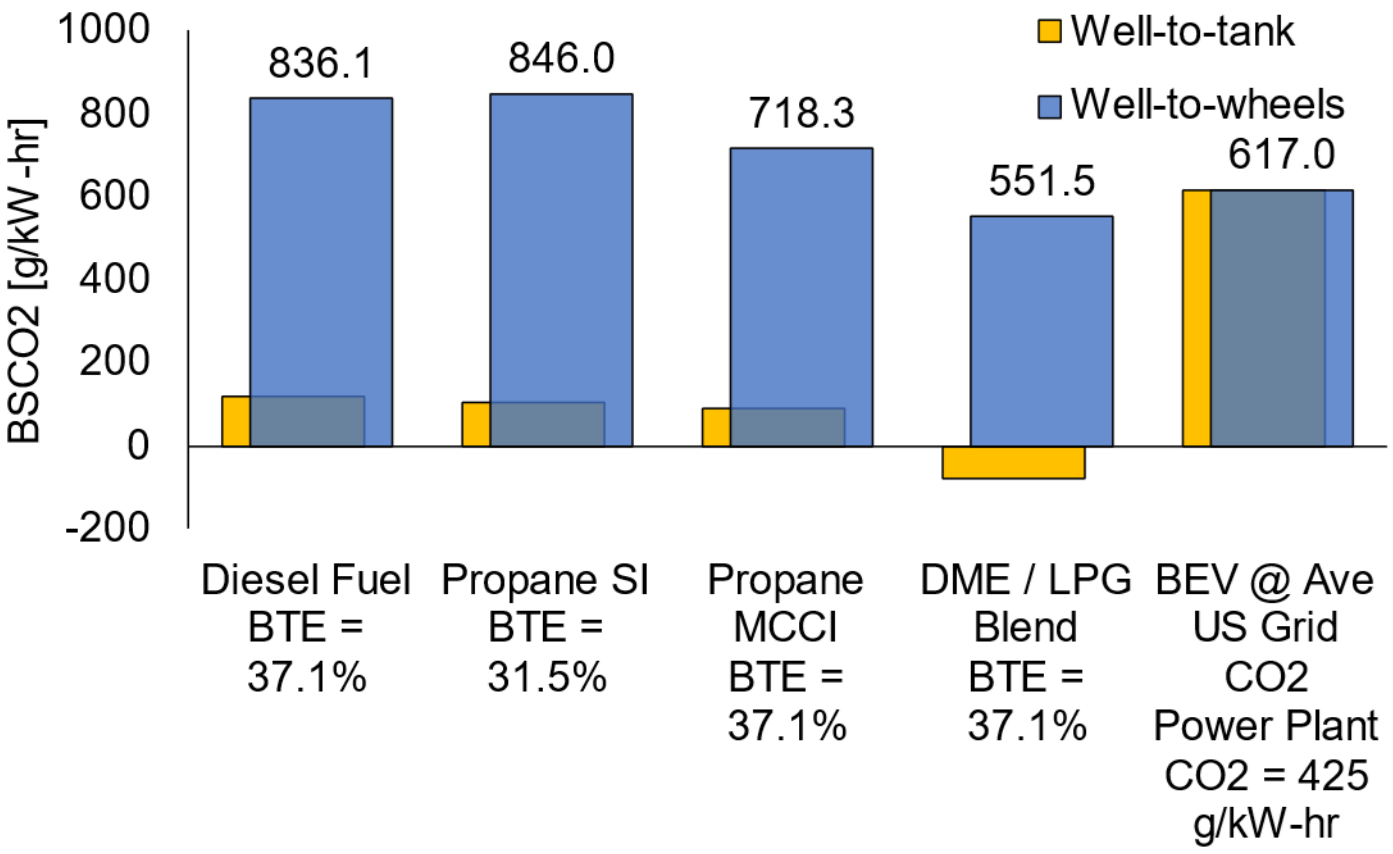
Objective: Collect emissions and performance data of propane MCCI combustion needed for model validation and pre-competitive assessment of optimized hardware configuration

Approach: Collect data needed for model validation and complete experiments to evaluate efficiency and emissions over a representative drive cycle.



Technical Accomplishments and Progress

- System level analysis was used to evaluate potential CO_2 reductions achievable using a propane / DME fueled engine
- Propane SI and current diesel fueled CI engines have similar well-to-wheels (WTW) CO_2
- Enabling CI efficiency in a propane fueled engine has the potential to reduce WTW CO_2 by 14% compared to current diesel fueled engines
- Blending 20% renewable DME with propane has the potential to reduce WTW CO_2 by over 30% compared to today's diesel engines
- The 20% renewable DME and propane engine has 10% lower CO_2 than a battery electric vehicle (BEV) charged using the US average grid **without** considering CO_2 of battery production

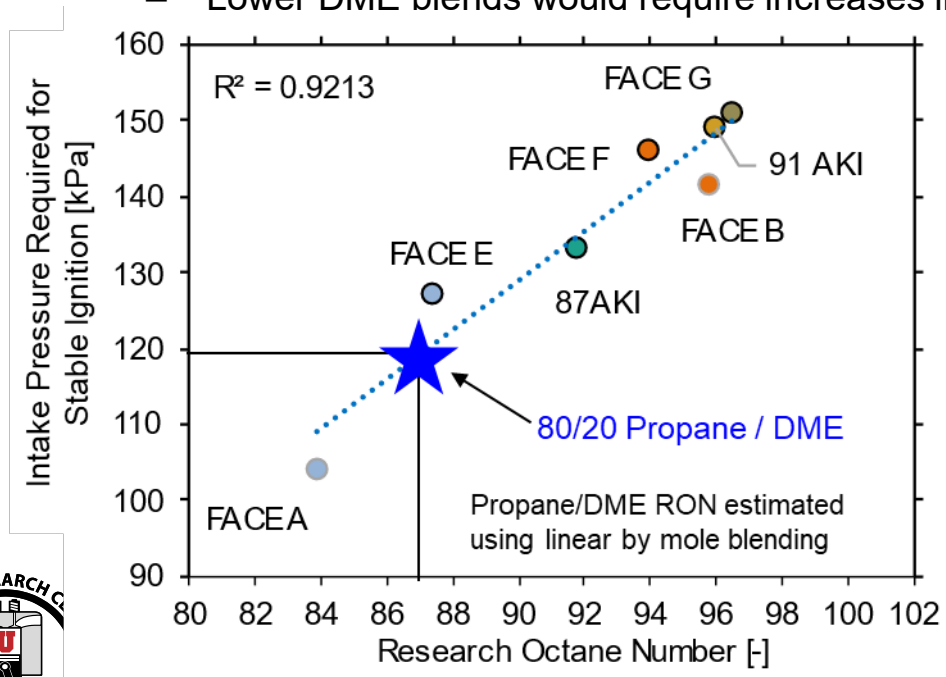


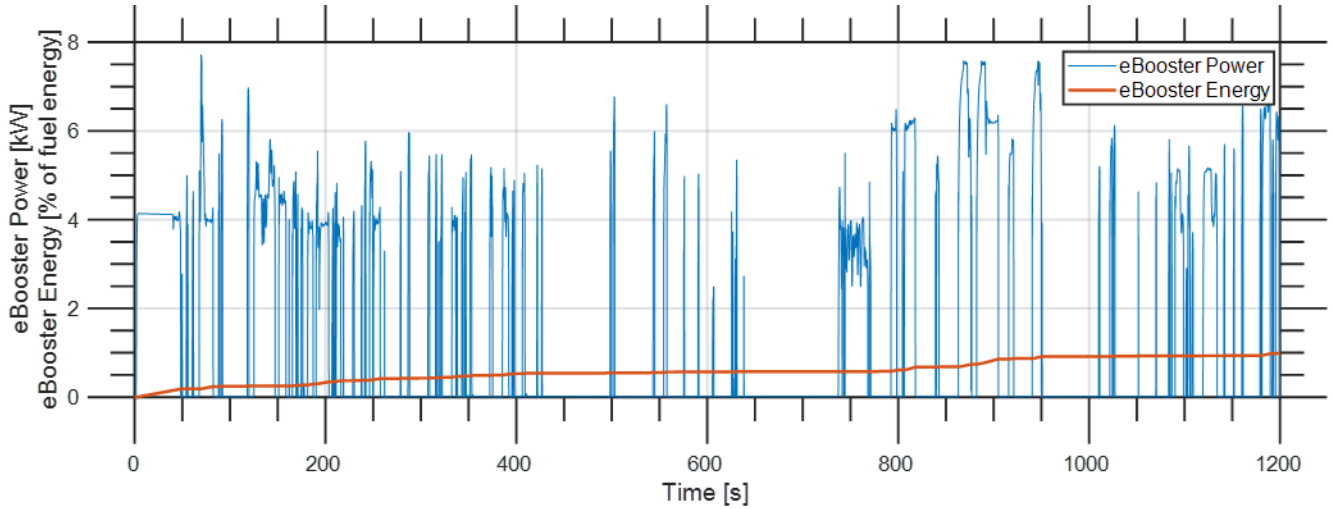
BEV assumptions: Powerplant CO2 = 425 g/kW-hr, transmission losses = 5%, charging efficiency = 85%, discharging efficiency = 90%, motor efficiency = 95%

Project start date is April 2022 and AMR slides due April 2022; accordingly, all progress is preliminary efforts

Technical Accomplishments and Progress

- Approaches to achieving robust MCCI combustion will build on our previous experience with gasoline MCCI combustion
- Previous work has shown that intake pressure is a promising approach to stabilize GCI combustion
  - Additional boost required below 3 bar BMEP to maintain stable ignition
  - Electric supercharger (eBooster) simulated in validated GT-Power model and used to compare GCI+eBooster combustion to diesel combustion for an off-highway engine (non-road transient cycle) → similar results are expected for propane/DME blends due to similar RON
  - Energy consumption over non-road transient cycle is equivalent to less than 1% of the fuel's energy
  - Lower DME blends would require increases in eBooster energy consumption





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Remaining Challenges and Barriers

Main Barriers

- Balancing the cost, complexity, durability, and efficiency of a propane-fueled MCCI powertrain to enable market acceptance → a systematic assessment is required to provide pre-competitive data that can be widely applied to both the on- and off-road markets

Technical Challenges

- Achieving stable ignition of propane at low load conditions
- Accuracy of propane chemistry → Most propane chemical kinetics models have been developed for low pressure conditions, efforts are needed to evaluate under MCCI relevant pressures
- Fabrication of hardware required for high pressure direct-injection of propane / DME blends
- Implementation of injection hardware and control into engine test cell

Proposed Future Research

Budget Period 1

- Complete preliminary fuel system design
- Complete low-pressure fuel system for metal engine test stand
- Complete procurement of high pressure fuel system components.
- Perform high-speed schlieren imaging results for jet development of three propane DME mixtures under non-reacting conditions.
- Finalize reduced DME-propane mechanism validated using shock tube experiments
- Demonstrate compression ignition operation on propane-DME blends to evaluate the operability of the engine and identify areas where operation is challenging

Any proposed future work is subject to change based on funding levels

Summary

Accomplishments

- Simulations suggest the potential for greater than 15% reduction in CO_2 emissions compared to a conventional diesel engine and a 10% reduction compared to a BEV

Approach

- Effort combines fundamental experiments (shock tube and optical engine), hardware development, and engine testing to evaluate approaches to use propane-DME blends in a mixing controlled combustion process
- Key outcome will be pre-competitive data to identify and evaluate a robust combustion strategy to enable mixing controlled compression ignition combustion of propane-DME blends

Relevance toward VTO objectives

- This program seeks to use simulation, optimization, engine, powertrain and vehicle testing to support development of an ultra-low CO_2 architecture that is capable of reducing fuel consumption and CO_2 emission for a broad range of medium-duty vehicles. The program seeks to identify and quantify tradeoffs between system efficiency, complexity, cost, and customer acceptance to provide insight into propane-DME fueled powertrain options.

Technical Back-Up Slides

Collaboration and Coordination

Team member	Location	Role in project
UW – Madison Engine Research Center	Madison, WI	Program Lead Combustion System Development
WM International	Darien, IL	Fuel System Development
University of Central Florida	Orlando, FL	Kinetics data and modeling
Wisconsin Engine Research Consultants	Madison, WI	CFD Optimization
Propane Education & Research Council (PERC)	Washington, DC	Financial Support and Propane Data
Oberon Fuels	San Diego CA	DME supply and fuel analysis

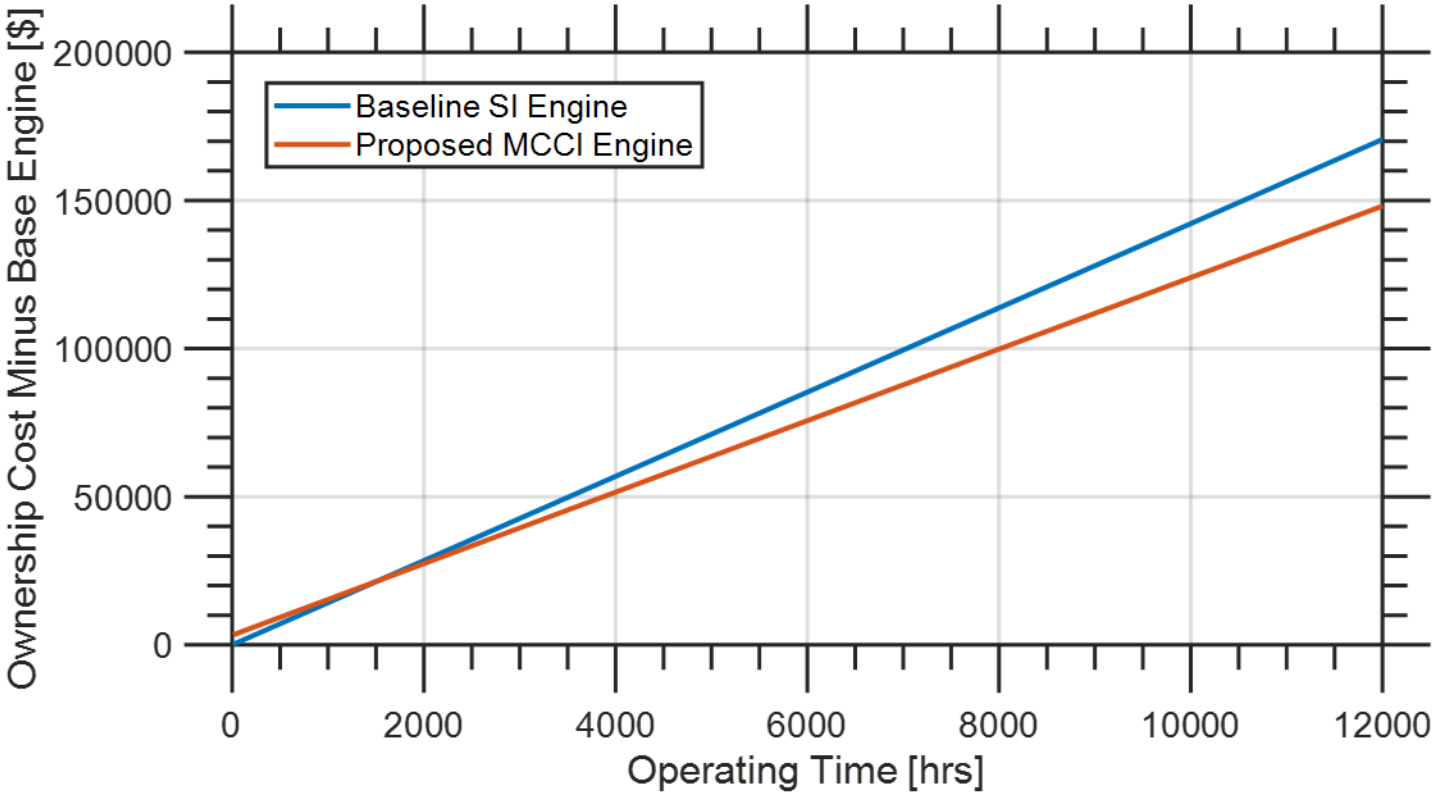
Milestones

Today

	BP1				BP2				BP3			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task 1 Fuel system development (Months 1 - 36)												
Subtask 1.1 Low-Pressure System Supply (Months 1-9)			M1.1.1									
Subtask 1.2 High Pressure Injection System (Months 1-10)			M1.2.1									
Subtask 1.3 Injector Driver and Pump Controls (Months 3-10)			M1.3.1									
Subtask 1.4 Fuel Injection System Calibration (Months 10-17)							M1.4.1					
Subtask 1.5 Installation of System at UWM (Months 12-24)					M1.5.1							
Subtask 1.6 Engine Support and Updates (Months 24-36)												
Task 2 Propane-DME Ignition delay Times and Speciation Measurements, Chemical Kinetics Model Development (month												
Subtask 2.1 Ignition Delay Times, 60-80 bar (Months 1-12)				M2.1.1								
Subtask 2.2. Ignition Delay Times, 100-120 bar (Months 13-24)								M2.2.1				
Subtask 2.3 Time-Resolved Species Measurements up to 60 bar											M2.3.1	
Task 3 Optical Engine Experiments (Months 1 - 36)												
Subtask 3.1 Installation of high-pressure propane-DME fuels system (Months 1-9)			M3.1.1									
Subtask 3.2 High-speed imaging of jet development and ignition				M3.2.1		M3.2.2						
Subtask 3.3 Optical engine glow plug and laser-ignition testing							M3.3.1		M3.3.2			
Subtask 3.4 High-speed PLIF imaging investigation (Months 28-36)										M3.4.1		M3.4.2
Task 4 Combustion Optimization (Months 13 - 22)												
Subtask 4.1 Spray model validation (Month 14)					M4.1.1							
Subtask 4.2 Baseline CFD model validation (Month 15)					M4.2.1							
Subtask 4.3 Fuel injection system optimization (Months 14 – 19)							M4.3.1					
Subtask 4.4 Piston bowl geometry optimization (Months 20 -22)								M4.4.1				
Task 5 Metal Engine Testing (Months 1 - 36)												
Subtask 5.1 Model validation experiments (Months 1-15)	M5.1	M5.1	M5.1	M5.1	M5.1.5							
Subtask 5.2 Hardware Modifications (Months 15 - 24)								M5.2.1				
Subtask 5.3 Demonstration experiments (Months 25-32)											M5.3.1	
Subtask 5.4 Multi-cylinder model construction (Months 32-35)												M5.4.1
Subtask 5.5 Technology Evaluation (M36)												M5.5.1

Technical Accomplishments and Progress

- Cost analysis shows MCCI powertrain expected to be ~$3,300 greater than SI engine due to aftertreatment and fuel system cost
- At current LPG prices, fuel savings result in a payback period of ~1500 hours (nominally 1.5 years)
- At 12000 hours, savings of greater than $20K expected



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