High BMEP and High Efficiency Micro-Pilot Ignition Natural Gas Engine

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Michigan Tech

Project ID: FT059

Westport™

Outline

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3. Milestones for FY 2017 and FY 2018
4. Approach
5. Technical Accomplishments and Progress
6. Responses to Previous Year Reviewers' Comments
   (NA – First year in review)
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Overview

Timeline

- Start Date: April 1, 2016
  - Budget Year 1 Extended by 3 Months
- End Date: June 30, 2019
- Percent Complete: 25%

Budget

- Requested DOE Funds / Share: $0.6M / 50%
- Proposed Applicant Funds / Share: $0.6M / 50%

Partners

- Westport Fuel Systems Inc.

Barriers

- Limitations for the ignition of small diesel quantities in a NG, air and EGR premixed mixture
- Ignition process sensitivity to fuel composition
- Optimum level of charge motion to maximize ignition over engine operation range
- Combustion sensitivity to knock or other forms of abnormal combustion and how it can be avoided
- Combination of all technical elements for a commercially feasible high performance, high efficiency, next generation natural gas engine

Relevance

Objective:

- High peak brake thermal efficiency (up to 44%) under the constraint of a diesel pilot contribution of 1-5% with a BMEP up to 25 bar on a Cummins ISB 6.7L engine

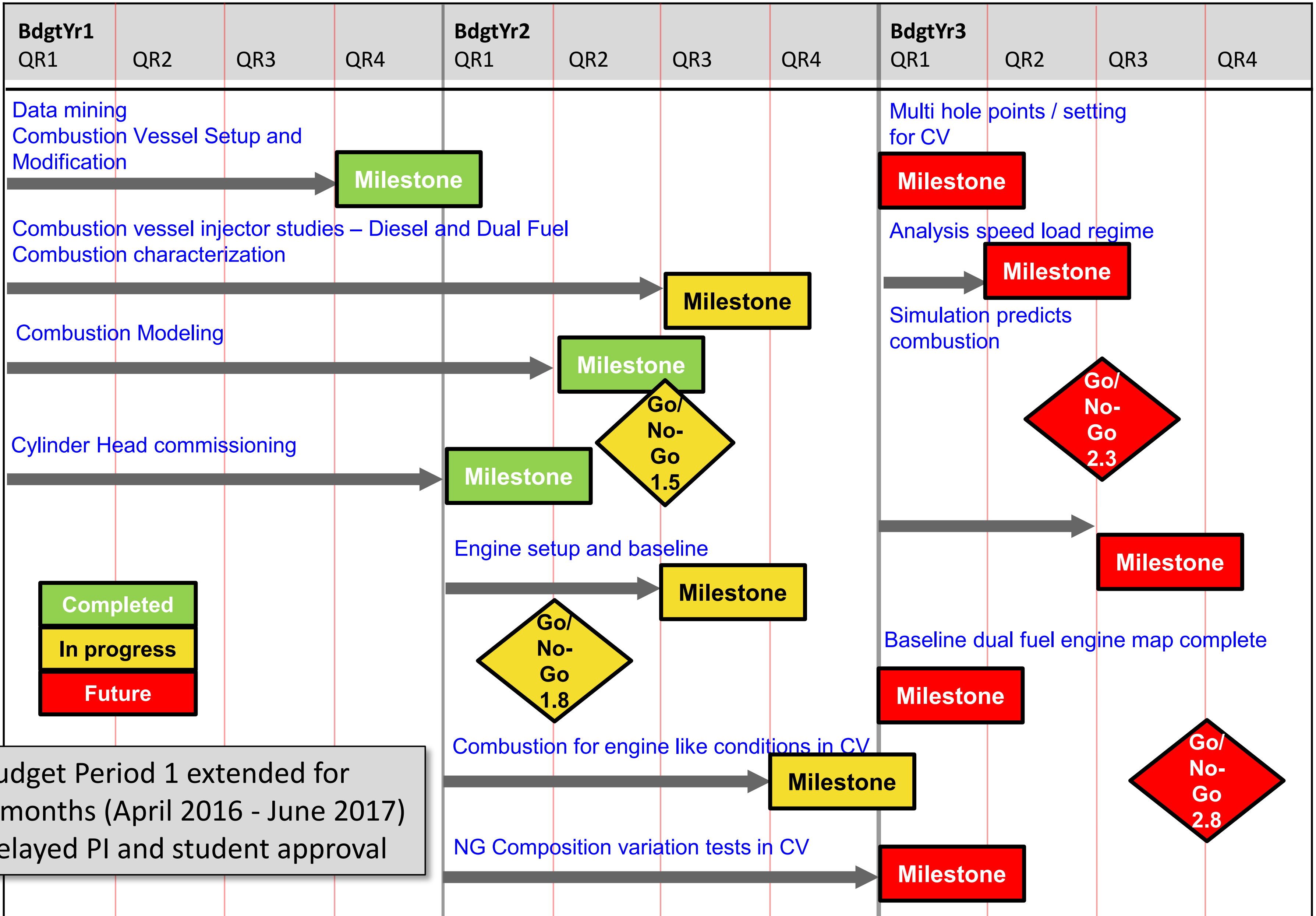
Impact:

- Energy opportunity for MHD natural gas vehicles:
  - 290,000 MD/HD trucks/year in 2020 x ≈ 15% NG penetration rate ≈ 43,500 trucks/year
  - Maximum total U.S. MHD Class 6/7/8 fuel savings opportunity ≈ 43,500 x (1,200 to 2,300)
  - DGE (6 – 11% F.E. improvements vs. incumbent SI NG) ≈ 52,000,000 – 98,000,000 DGE/year
  - 10 - 15% CO_2 improvement vs. diesel engine ≈ 23 - 34 tons/truck/year
  - Maximum total U.S. MHD Class 6/7/8 CO_2 savings opportunity ≈ 1.0 – 1.5 MMtons/year

Milestones for FY 2017 and FY 2018

Date	Milestones	Status
October 2016	M1.1: Data Mining, Analysis and Literature Review	Complete
January 2017	M1.2: Combustion Vessel Setup & Baseline – Combustion vessel modification	Complete
June 2017	M1.3: Combustion Vessel Setup & Baseline – Injector Studies	On track
March 2017	M1.4: Combustion Modeling - Thermo-kinetic modeling of micro-pilot ignition and combustion	Complete
June 2017	M1.5:Combustion Modeling	On track
October 2016	M1.6: Engine Setup and Baseline Testing	Complete
June 2017	M1.7: Engine Setup and Baseline Testing	On Track
June 2017	M1.8: Engine Setup and Baseline	On Track
September 2017	M2.1: Control variables for engine-like conditions in CV	On Track
December 2017	M2.2: NG composition variations tested in CV	On Track
June 2018	G/N2.3: Ignition limitation understood	On Track
December 2017	M2.4: Multi-mode points/settings for engine	On Track
March 2018	M2.5: Analysis speed/load regimes	On Track
June 2018	G/N2.6: Simulation accurately predicts combustion	On Track
December 2017	M2.7: Baseline engine mapping complete	On Track
June 2018	G/N2.8: Phase 3 testing recommendations in project scope	On Track

Approach

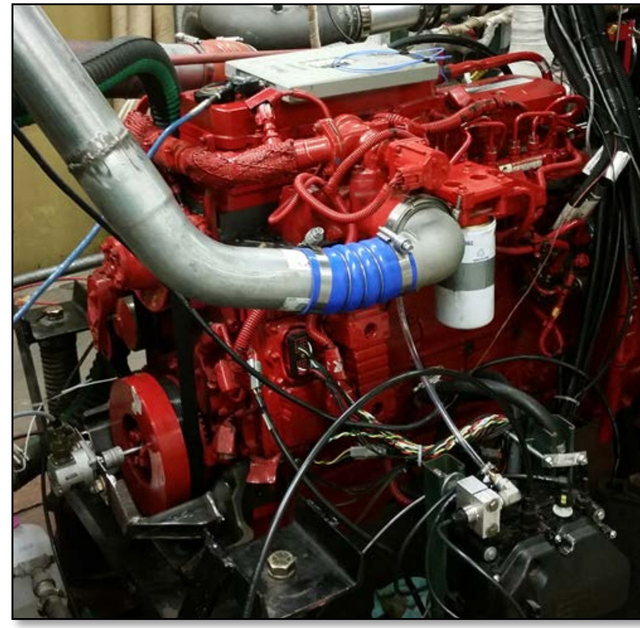


Budget Period 1 extended for
3 months (April 2016 - June 2017)
Delayed PI and student approval

TECHNICAL ACCOMPLISHMENTS AND PROGRESS

Engine Studies Accomplishments: Engine Description and instrumentation

Model	Cummins ISB 224kW (300 hp)
Cylinders	6
Bore & Stroke	107 x 124mm
Connecting rod length	192 mm
Displacement	6.7 L
Compression Ratio	17.3 : 1
Aspiration	VFT + Charge Air Cooler + HPL EGR
Rated Power	224 kW @ 2600 RPM
Rated Torque	895 N-m @ 1600 RPM



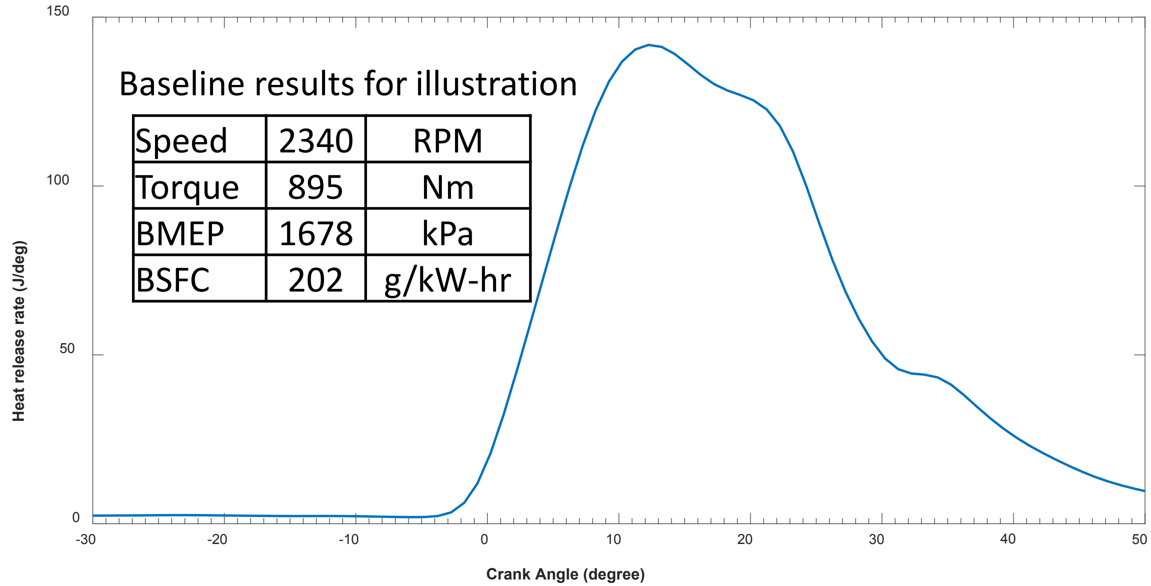
Instrumentation:

Sensor Type	Manufacturer	Part No.	Range	Unit	Sensor Output
Pressure Transducer w/ Heat Shield	AVL	GH15D + PH08	0-250	bar	19 pC/bar
Absolute Pressure Transducer	OMEGA	PX309-050A5V	0-3.4	bar	0-5 V
Current Probe	Fluke	80i-110s	0 – 100	A	10 mV/A
Encoder	BEI	H25DSS360ABZ	360 : 1	S/rev	Vout = Vin

- Emissions measurements through 5 gas analyzer and Bosch smoke meter

Engine Studies Accomplishments: Engine Test Conditions and Results

- ✓ Baseline tests for simulation model validation and dual fuel comparison
- ✓ Actuator sensitivity studies to support simulation and understand engine response for charge control

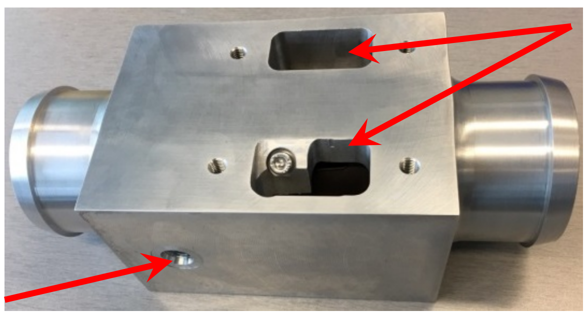


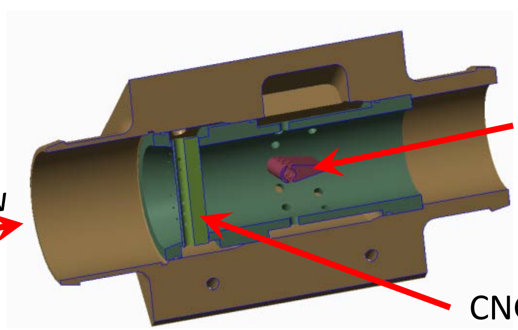
Actuator Sensitivity Testing		
Test mode	**Condition**	
Engine response to VGT position	Low Load (25%) Low Speed (35%)	VGT range from 100% to 0% / 0% EGR
	Mid Load (50%) Mid Speed (50%)	VGT range from 100% to 0% / 0% EGR
	High Load (100%) Low Speed (35%)	VGT range from 100% to 0% / 0% EGR
Engine response to EGR quantity	Low Load (25%) Low Speed (35%)	EGR range from 40% to 0%
	Mid Load (50%) Mid Speed (50%)	EGR range from 40% to 0%
	High Load (100%) Low Speed (35%)	EGR range from 40% to 0%

CNG Fuel System Development – Westport™

CNG/EGR mixer:

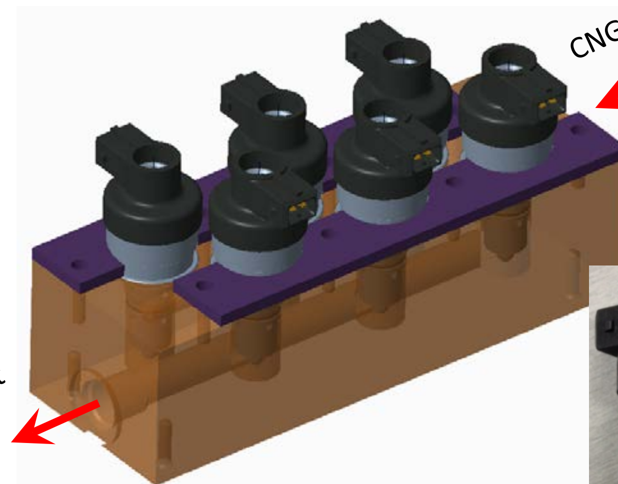
- Evaluated single point and multi-point injection.
- Homogeneous mixture of air, CNG, & EGR essential.
- Designed & fabricated a mixer for the CNG and EGR for inlet duct of engine.





CNG injectors and mounting rail:

- Evaluated flow requirements and selected the CNG injectors (6 per engine).
- Designed and fabricated a manifold and rail assembly to house the injectors.



Injector manifold and rail assembly

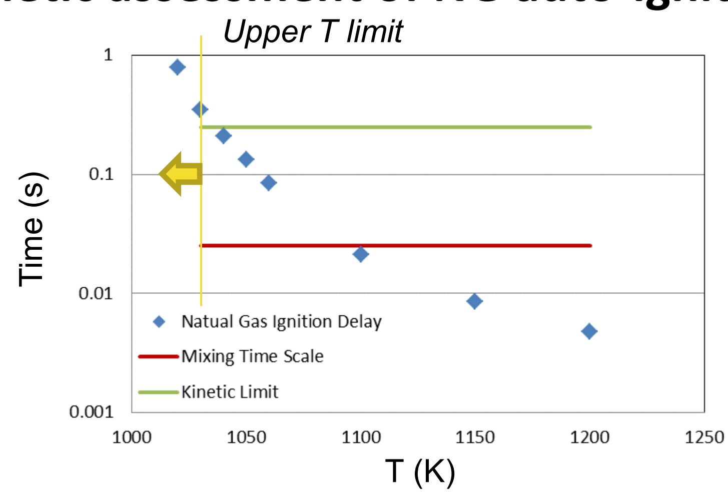
CNG Injector

Combustion vessel modelling: kinetics and mixing – Westport™

CV evaluation of pilot ignition delay in premixed natural gas/EGR mixture

- NG must be injected after pre-burn, with enough time for mixing before pilot injection
- NG injection must be into low-enough temperature that auto-ignition of the NG does not occur

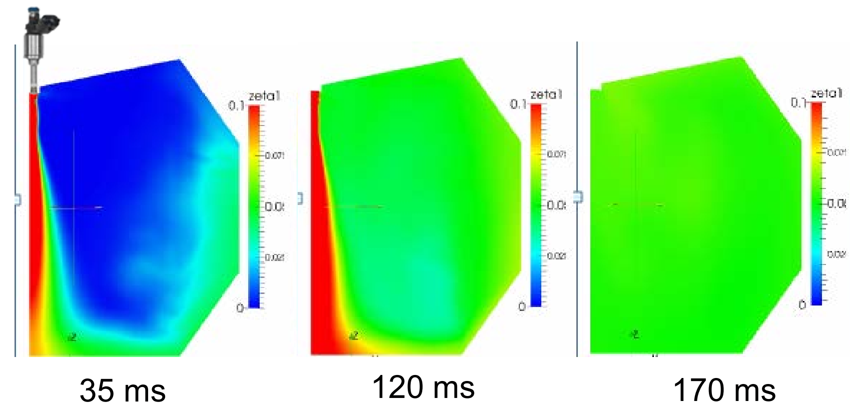
Kinetic assessment of NG auto-ignition:

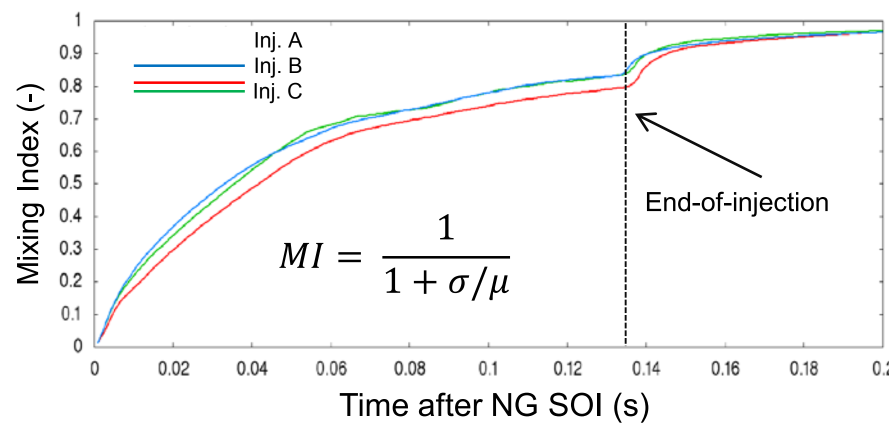


To avoid NG auto-ignition,
need chamber T < 1030 K at gas SOI

NG mixing: Evaluate mixing index for different injector geometries (200 bar gas, 100 bar chamber)

Mixture fraction (Z) during and after injection



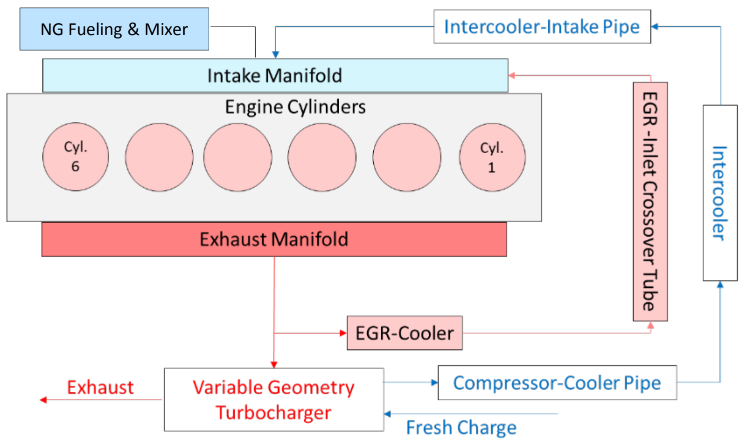


1D Simulation Accomplishments: Model validation and dual fuel mode development

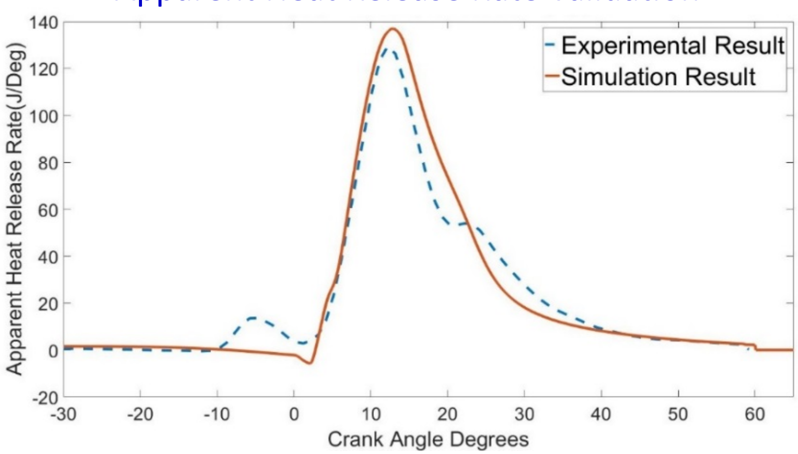
- 1D Diesel engine model calibrated from baseline tests

Parameter	Experimental	Simulation	Difference
Speed	1768		0
EGR(%)	17		0
Torque(N-m)	450	441	9
IMEP	9.29	9.52	-0.23
A/F Ratio	24.9	24.2	0.4
Max Cylinder Pressure(bar)	84.4	83.5	0.9
CAD for Pmax (deg ATDC)	14	15	1
NOx (ppm)	219	226	-7

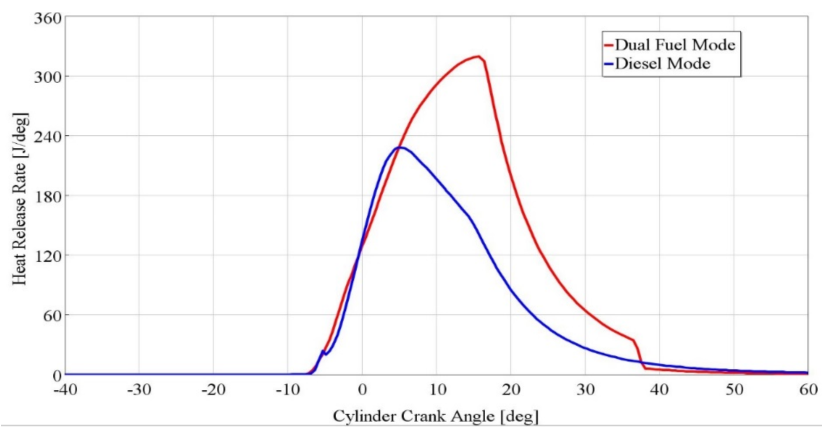
- Model for dual fuel engine in progress



Apparent Heat Release Rate Validation

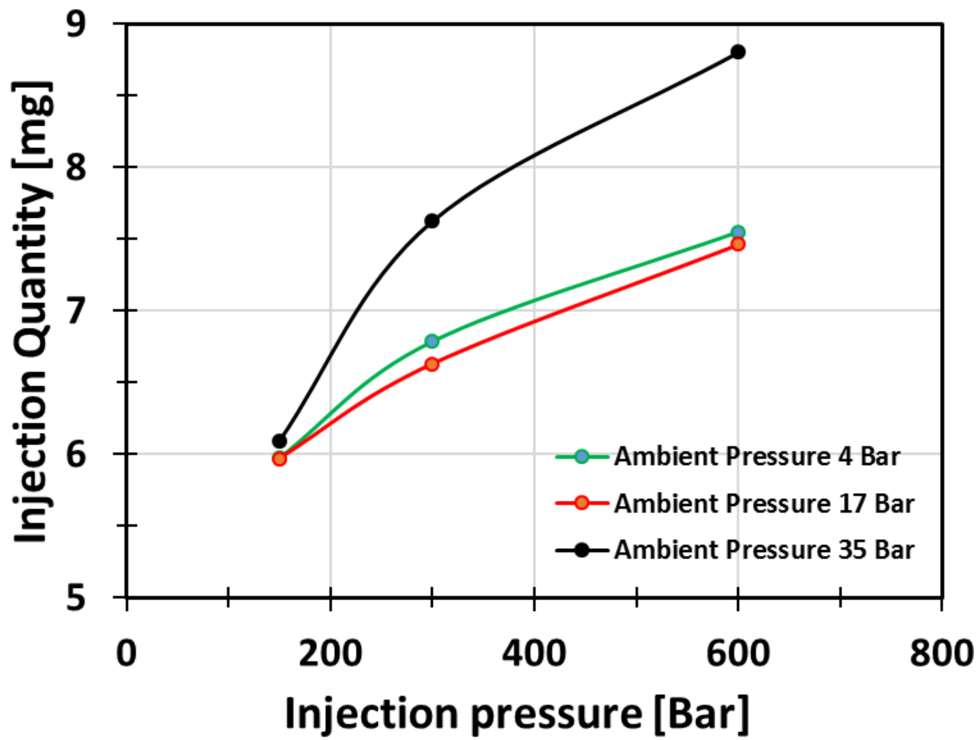


Apparent Heat Release Rate Comparison



Spray and Combustion Studies Accomplishments: Minimum Injection Quantity Investigation

Ambient pressure	Injection pressure	*EID	Injection Quantity
Bar	Bar	ms	mg
4	150	0.25	6.56
	300	0.20	6.79
	600	*0.15	6.60
17	150	0.25	5.97
	300	0.20	6.63
	600	0.15	7.46
35	150	0.25	6.09
	300	0.20	7.62
	600	0.15	8.80



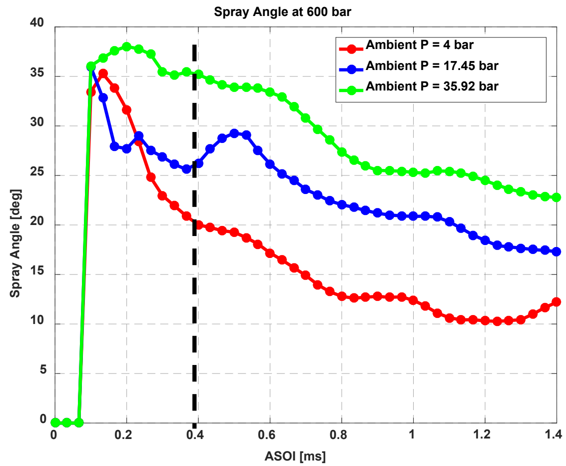
Baseline engine testing data:

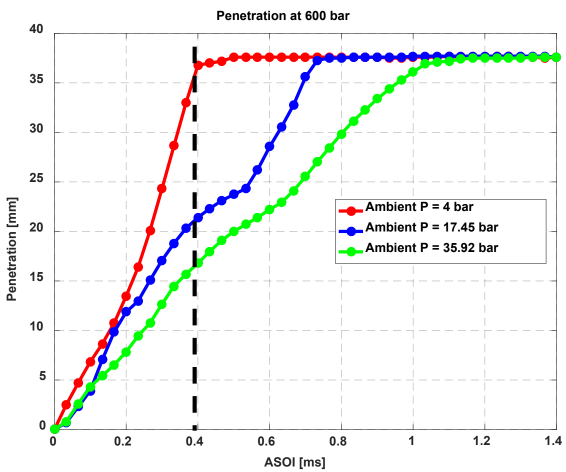
Load	speed	IMEP	Total fuel
N-m	RPM	Bar	mg/stroke
223	1211	5.7	34

- Minimum Injection Quantity: 6 mg/stroke/injector @150 bar, 0.28 ms Hydraulic duration, 17.5 bar ambient pressure.
- Targeted fuel quantity: 34·5% =1.7 mg/stroke/injector

*EID: Electrical Injection Duration
*0.15 ms is minimum repeatable duration

Spray and Combustion Studies: Spray Angle and Penetration





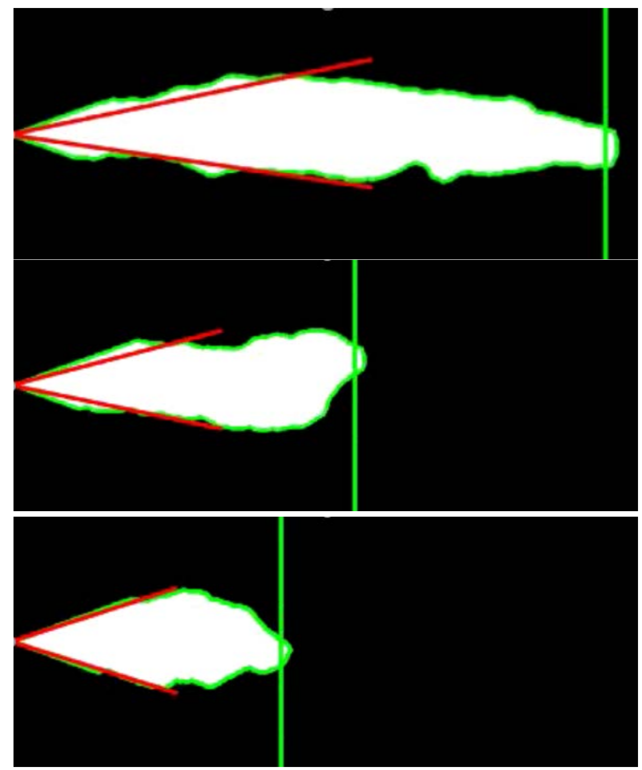
Injection Pressure = 600 bar, EID = 1.2 ms, 30k FPS, F/11, Shutter 32.67 us

ASOI = 0.4 ms

$P_{ambt} = 4\ bar$

$P_{ambt} = 17\ bar$

$P_{ambt} = 35\ bar$



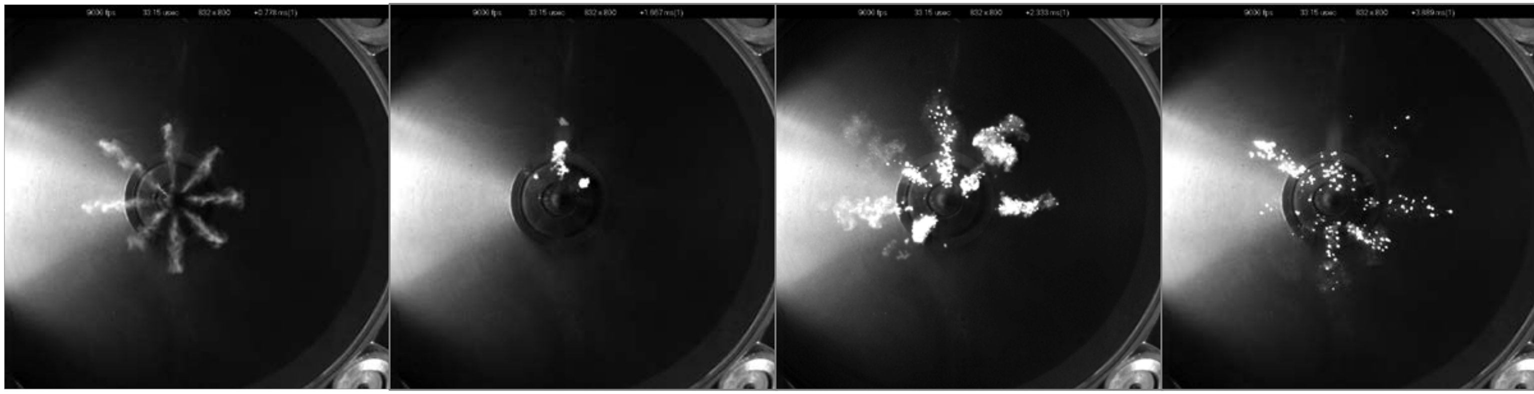
EID = Electronic Injection Duration

Spray and Combustion Studies

21% O2 concentration, bulk density= 13 kg/m³, Core temperature=800 K

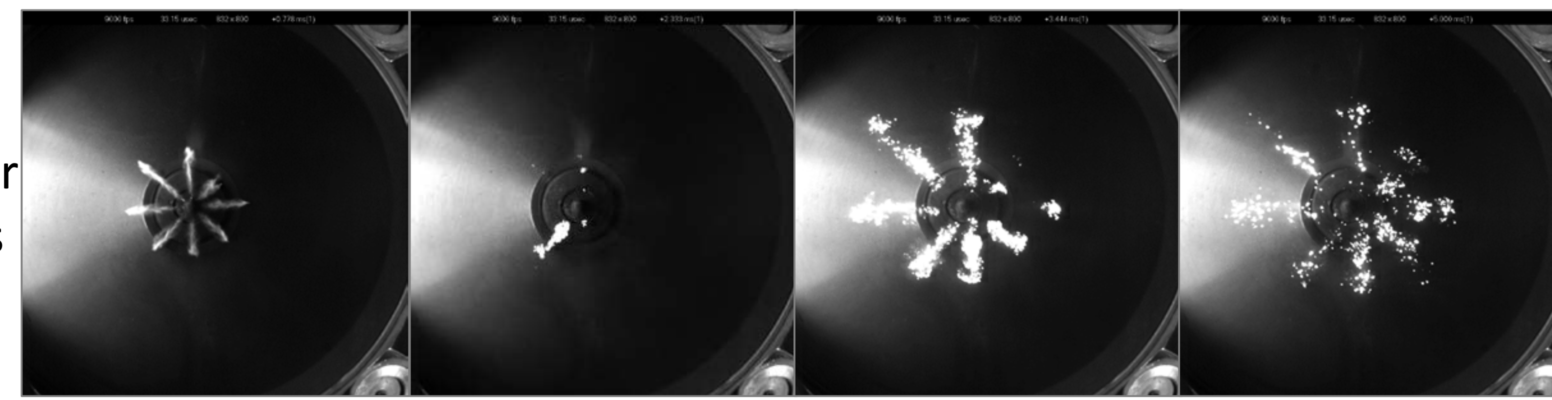
ASOI (ms) 0.78 1.67 2.33 3.89

P_{INJ} = 600 bar
EID=0.28 ms



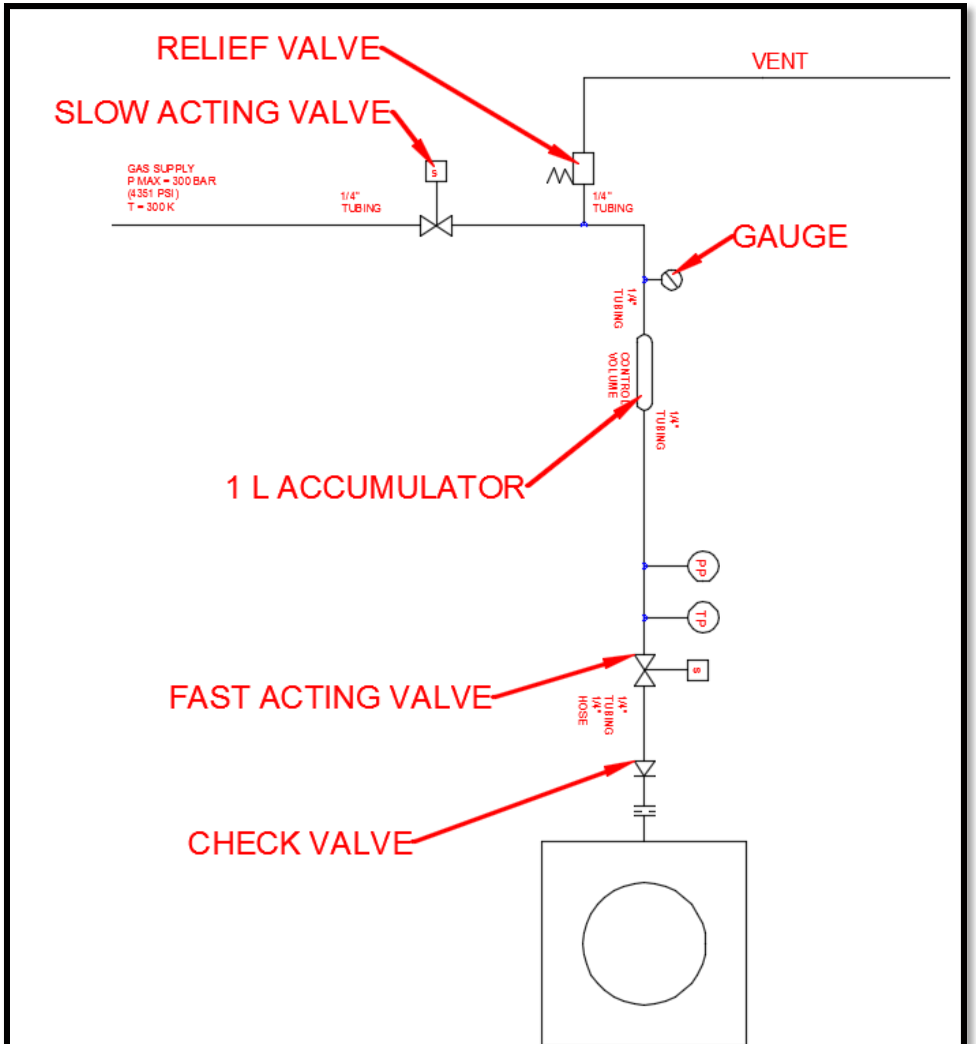
ASOI (ms) 0.78 2.33 3.44 5.00

P_{INJ} = 300 bar
EID=0.40 ms



EID = Electronic Injection Duration

NG Injection System for Dual Fuel CV Studies



Feeds multiple nozzles/injectors @ 340 bar

Collaboration with Other Institutions – Westport™

- Providing computational fluid dynamics (CFD) models and simulation to support spray & combustion investigation and engine studies in dual fuel mode.
- Providing solutions and parts for the modification of engine`s fuel system for dual fuel mode.
- Providing relevant Natural Gas engine data to support engine`s 1D simulation and defining test conditions for spray and combustion and engine studies.
- Providing insights of natural gas engine operations and performance.

Remaining Challenges and Barriers

- Diesel Micro Pilot Ignition
  - Need of diesel injector design capable of delivering small fuel injection quantities
- Premix Natural Gas Charge
  - Validation of premixed air and natural gas charge resistance to auto-ignition under diesel-like in cylinder conditions
  - Natural gas and air charge combustion control with cooled EGR and micro-pilot injection 1 – 5%
- Dual Fuel Engine Conversion and Control
  - Conversion of a commercial MD ISB 6.7L diesel engine into a dual fuel engine, the challenge is to install and commission NG fuel system and developing charge control to achieve the target BMEP
  - Development of the software strategies and calibrations to convert a stock diesel only engine to dual fuel NG / Diesel using prototype controller

Proposed Future Research for FY17 and FY18

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

Micro pilot injection characterization:

- Selection of diesel injector capable of delivering small fuel quantities
- Characterization of micro pilot spray and combustion in premixed air and natural gas charge under engine-like pressure and temperature condition with dilution. Including parametric studies of the dual fuel combustion and fuel sensitivity in a constant volume combustion vessel

- Combustion modeling and engine simulation:
  - Utilize the developed Computational Fluid Dynamics (CFD) model for the combustion vessel and engine combustion chamber along with the 1D engine simulation model to support and help predict studies of the dual fuel mode combustion
- Dual fuel engine commissioning / Tuning and mapping:
  - Modification of commercial diesel engine to dual fuel mode will involve the fuel system modification, the engine strategy software development and validation, and the selection of a TWC
  - Mapping and tuning the modified engine under dual fuel mode

Summary

- **Objective**
  - High peak brake thermal efficiency (up to 44%) under the constraint of a diesel pilot contribution of 1-5% with a BMEP up to 25 bar on a Cummins ISB 6.7L engine
- **Approach**
  - **Stoichiometric fueling**
  - **1-5% pilot energy ratio of diesel**
  - **VVA** to optimize charge handling
  - **Charge dilution** for low temperature combustion and reduced potential of knock
  - **Ultra lean operation** for certain low load conditions potential of micro pilot combustion stability

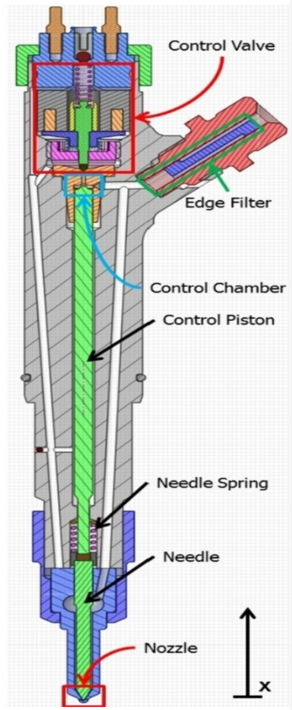
- **Accomplishments**
  - Stock diesel engine baseline and sensitivity tests complete
  - Modification of the Combustion vessel to accommodate the stock diesel injector and NG injection
  - Stock injector combustion characterization and minimum injection capability studies
  - 1D engine simulation and CFD model development and validation
- **Future work**
  - Micro pilot injection characterization
  - Combustion modeling and simulation
  - Engine commissioning and conversion to dual fuel mode

TECHNICAL BACKUP SLIDES

1D Simulation Model Calibration Procedure

Engine Experimental Data

Injection Profile Rate Map



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Model Calibration

- Design of Experiments to optimize the combustion and NOx multipliers
  - Entrainment Rate
  - Ignition Delay
  - Premix Combustion
  - Diffusion Combustion
  - NOx Calibration
- Multipliers chosen to minimize Burn rate error (%)