Direct Injection 4.3 L Propane Engine Research, Development, and Testing

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DOE Vehicle Technologies Program
2019 Annual Merit Review and Peer Evaluation Meeting

Project ID # ft081

Overview

Timeline

- Project start date: July 2017
- Project end date: July 2020
- Percent complete: ~60%

Budget

- Total project funding: $3,231,643
  - DOE share: $2,064,117
  - Contractor share: $1,167,526
- Project funding above was based on FOA award, subsequently under revision

FOA: Funding opportunity announcement
NREL: National Renewable Energy Laboratory
ORNL: Oak Ridge National Laboratory

Barriers

- Direct fuel injection technology is a technical barrier for propane engines as they are primarily based on gasoline engines, which have increasingly shifted from port injection to direct injection (DI)
- Emissions controls to enable mono-fuel (vs. bi-fuel) propane operation with DI are necessary

Partners

- NREL, ORNL, University of Alabama
- Industry collaboration
  - Blossman Services, Inc.
  - Freightliner
  - United Parcel Service (UPS)
  - Vieletech

Relevance

- This project was originally developed as a proposal to a DOE Vehicle Technologies Office (VTO) FOA area of interest to fund:
  - **Research, development, and demonstration of a direct injection (DI) propane engine for an on-road vehicle** approved for highway use...
  - Includes light, **medium**, and heavy-duty applications…
  - Based on a **currently-available commercial engine**...
  - Include **demonstration of engine in a vehicle or on a test stand** and must be **combined with a vehicle simulation** in the Argonne National Laboratory Autonomie Vehicle Modeling & Simulation Platform or similar tool…
  - Must meet current **U.S. standards for criteria pollutants**.

Relevance

- An industry-led team successfully proposed:
  - Research and development for **mono-fuel DI propane variant of General Motors 4.3L V6** gasoline spark ignition direct injection (SIDI) engine…
  - Including **critical high pressure fuel system controls for DI propane**…
  - Minimizing hardware changes (pistons and cylinder heads) to **enable post-project commercialization**…
  - **Exhaust aftertreatment** research and development for mono-fuel DI propane operation, including industry **guidance on particulate matter emissions**…
  - Meeting **Environmental Protection Agency (EPA) Phase 2** medium-duty / heavy-duty regulations…
  - Demonstrating at least a **20% greenhouse gas (GHG) improvement** (with a stretch goal of 30%) over a baseline gasoline engine version on a **custom drive cycle** representing package delivery truck operations…
  - **Integrated into a Freightliner MT-55** commercial truck…
  - **Demonstrated in fleet use with UPS**…
  - With comparative **chassis dynamometer GHG studies** to feed back into Autonomie.

Relevance

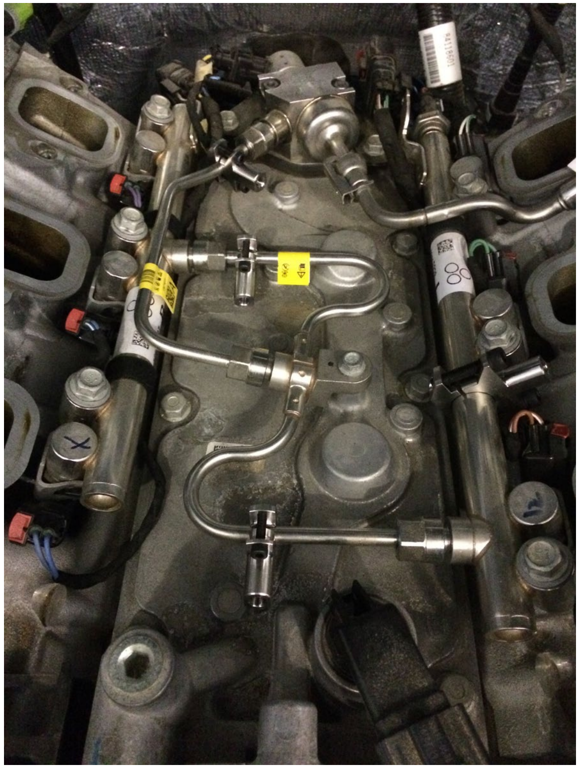
- After key go/no-go decision, project transitioned to a DOE lab + University effort:
  - Research and development for **mono-fuel DI propane variant of General Motors 4.3L V6** gasoline spark ignition direct injection (SIDI) engine…
  - Including **critical high pressure fuel system controls for DI propane**…
  - **Exhaust aftertreatment** research and development for mono-fuel DI propane operation, including industry **guidance on particulate matter emissions**…

- While still retaining key industry input and collaboration, the revised project still addresses most of industry and VTO's interests:
  - **Research, development, and demonstration of a direct injection (DI) propane engine for an on-road vehicle** approved for highway use...
  - Includes light, **medium**, and heavy-duty applications…
  - Based on a **currently-available commercial engine**…

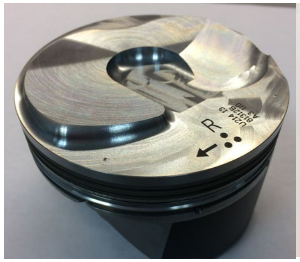
The critical technical barriers of adapting DI technology for propane engines with integrated aftertreatment still remains the focus of the revised project.

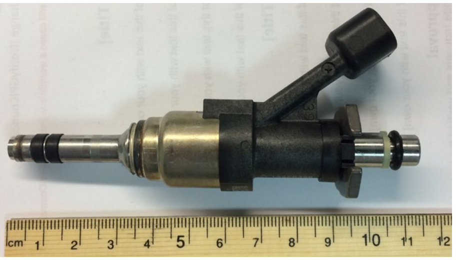
Approach

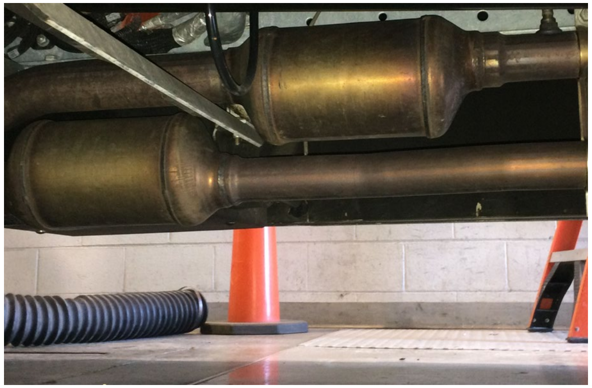
- Identify vehicle design and performance requirements from UPS and Freightliner
- Baseline comparative 6.0L V8 port fuel injection (PFI) gasoline UPS truck performance, emissions, GHGs
- Baseline 4.3L V6 SIDI performance on gasoline
- Evaluate vehicle simulations with 4.3L DI propane



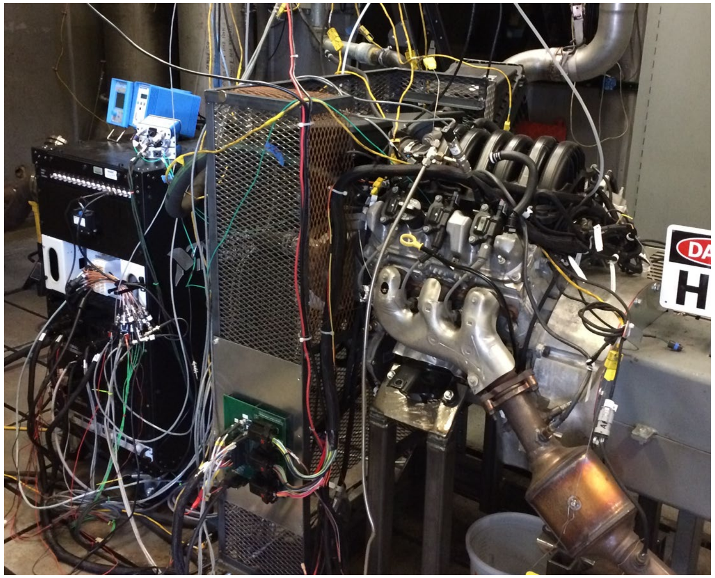
- Develop high pressure fuel system (pump, fuel rails, injectors) + tank integration simulations and combustion models to understand propane vs. gasoline differences
- Develop DI propane specific hardware and software controls and calibration – no changes to injectors
- Develop mono-fuel propane emissions control strategy and hardware







Approach



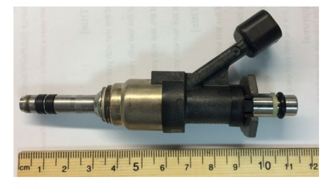
- Conduct informative particulate matter emissions studies
- *Demonstrate capability of meeting EPA certification requirements on medium-duty engine cycle (not an official certification)*
- *Integrate prototype engine + independent engine controls into Freightliner MT-55 truck for UPS*
- *Conduct chassis dynamometer studies to verify GHG improvement*

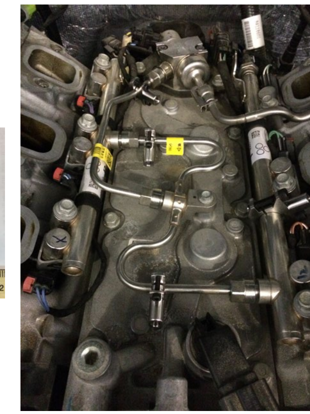
- *Operate prototype vehicle in UPS fleet operations with data loggers*
- *Feed engine and chassis dynamometer data from DI propane 4.3L V6 (and comparative 6.0L V8 PFI gasoline) to Autonomie simulations*
- *Enable post-project potential for commercialization (durability, certification) for UPS type applications*

Approach - Milestones

- Develop custom package delivery chassis dynamometer drive cycle - **December 2017 milestone**

- Develop initial 1-dimensional model of 4.3L high pressure fuel system (pump, fuel rails, injectors) - **April 2018 milestone**





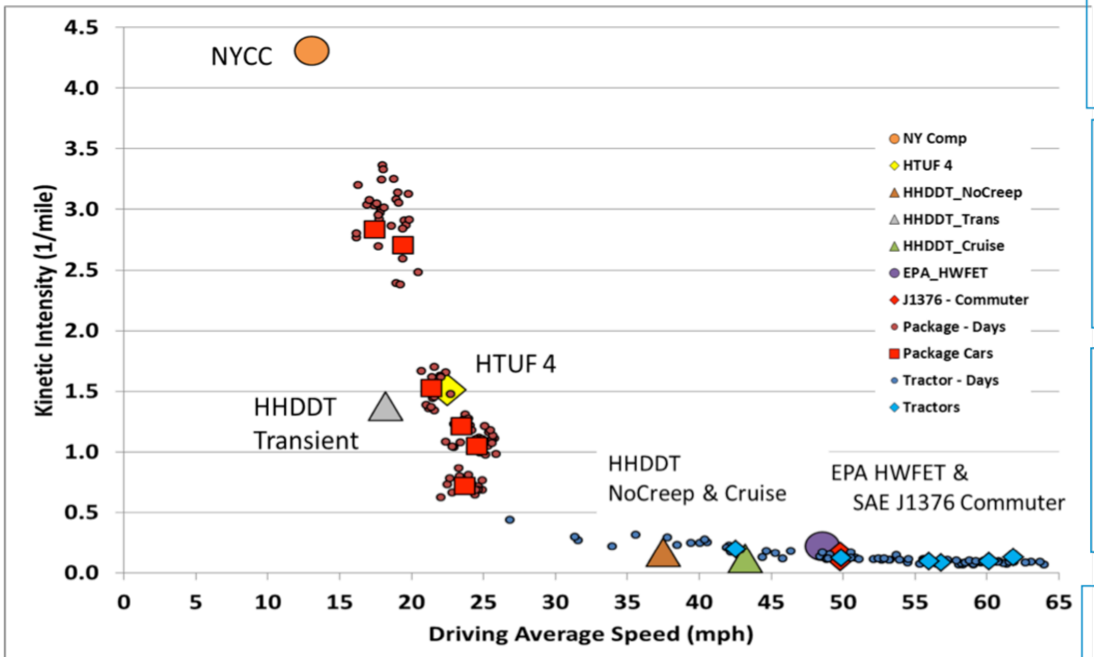
- Baseline 4.3L V6 SIDI performance on gasoline and project DI propane engine performance - **June 2018 milestone**

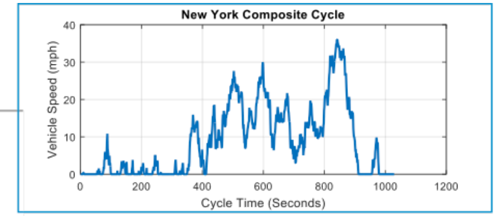
- Evaluation of 4.3L DI engine applicability - **December 2018 Go/No-Go milestone decision**

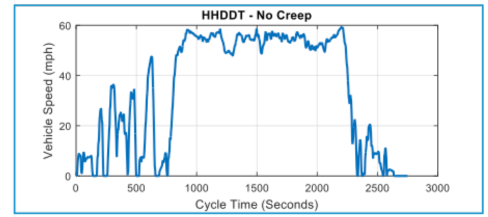
The FOA project award ended, but NREL, ORNL, U. Alabama, and Vieletech (with industry input) are continuing core research – New milestones under development.

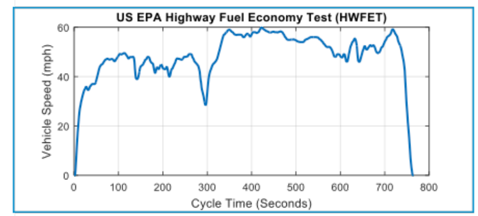
Technical Accomplishments and Progress

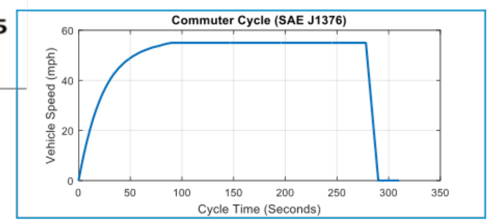
Custom ”package delivery” chassis dynamometer drive cycle enabled relevant GHG studies











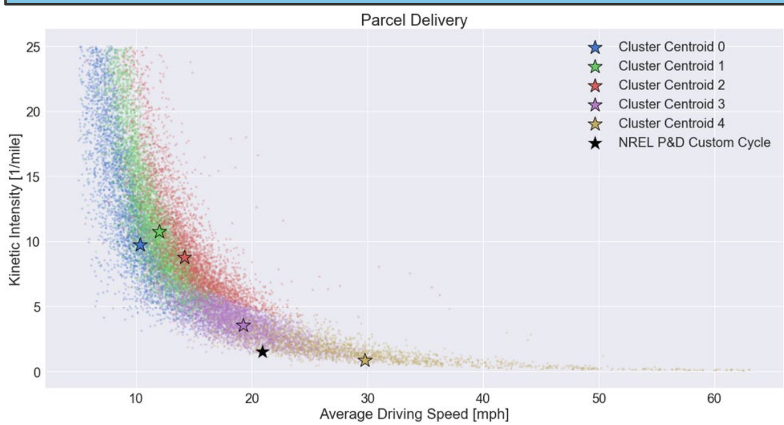
HHDDT: Heavy heavy-duty diesel truck
HWFET: Highway fuel economy test
HTUF: Hybrid truck users forum

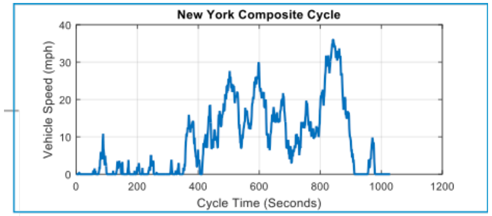
HTUF: Hybrid truck users forum
mph: Miles per hour
NYCC: New York city composite

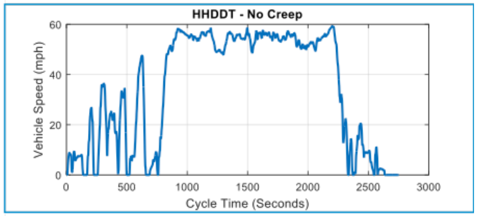
- Existing standardized chassis dynamometer drive cycles did not accurately represent real-world package delivery truck drive data.
- Developing a new cycle was necessary for UPS and Freightliner to understand potential GHG impact of the 4.3L DI propane engine versus 6.0L PFI gasoline baseline in this application.

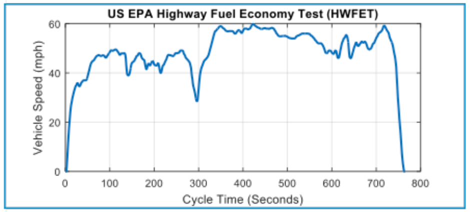
Technical Accomplishments and Progress

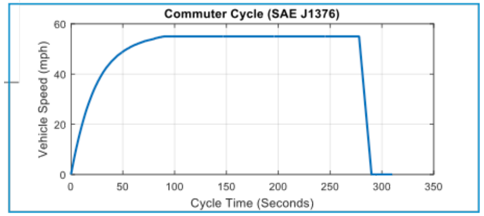
Custom ”package delivery” chassis dynamometer drive cycle enabled relevant GHG studies









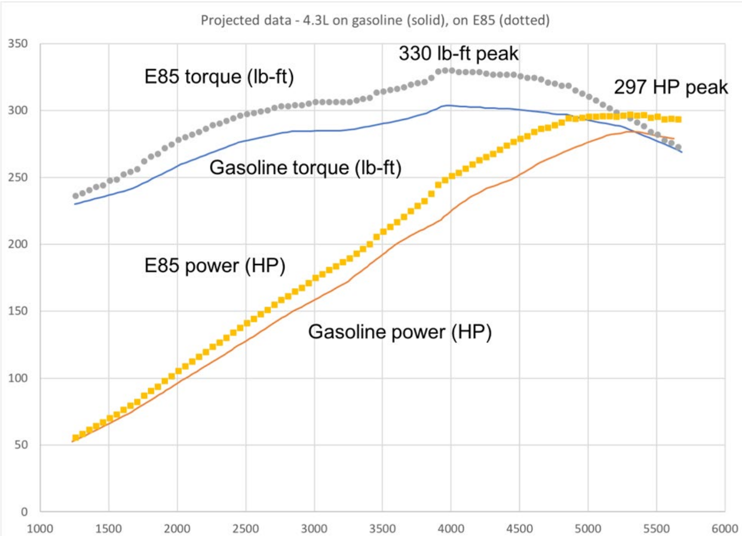


Hz: Hertz
min: Minutes
P&D: Parcel and delivery

- NREL’s Drive-Cycle Rapid Investigation, Visualization, and Evaluation (DRIVE) analysis tool was applied to in-use 1 Hz data collected for 1,300 days in 90 Class 5/6 package delivery vehicles in NREL’s Fleet DNA database (76 of 90 vehicles were UPS).
- New NREL package delivery cycle was used for this project, and the cycle itself is published.

Technical Accomplishments and Progress

Vehicle performance was projected with 4.3L DI propane to inform go/no-go decision



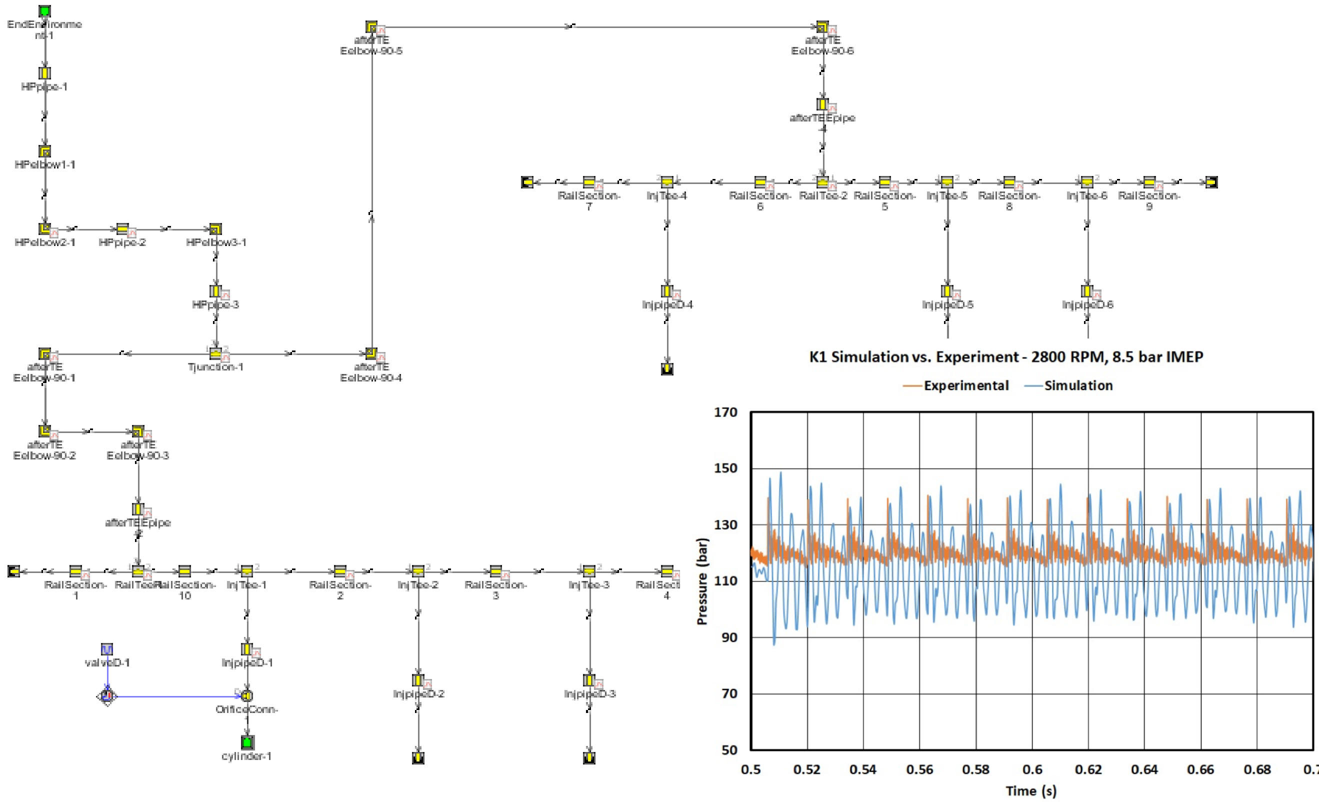
E85: Ethanol flex-fuel
GVW: Gross vehicle weight
HP: Horsepower
MPH: Miles per hour
WOT: Wide open throttle
#: Pound

- NREL projected 4.3L engine torque and power using E85, with which General Motors enables higher output in the Chevrolet Silverado. Propane DI performance was estimated to match E85-enabled levels.
- NREL and Freightliner performed WOT vehicle simulations for projected 4.3L DI propane versus baseline 6.0L PFI gasoline with 23,000 # GVW (~12,500 # payload... heavily loaded).
- 0-30 MPH, 0-60 MPH, and maximum maintainable speed at 3%, 6%, and 9% grade evaluated.
- 4.3L DI propane 0-30 MPH was projected at ~23% slower, 0-60 MPH at ~17% slower, and no gradeability change... acceptable performance given the GHG benefit.
- Go/no-go decision to stop was ultimately based on unknown 4.3L durability as a medium duty engine, risking post-project commercialization to the industry partners.

Technical Accomplishments and Progress

High pressure DI system dynamics for gasoline mapped and propane performance modeled

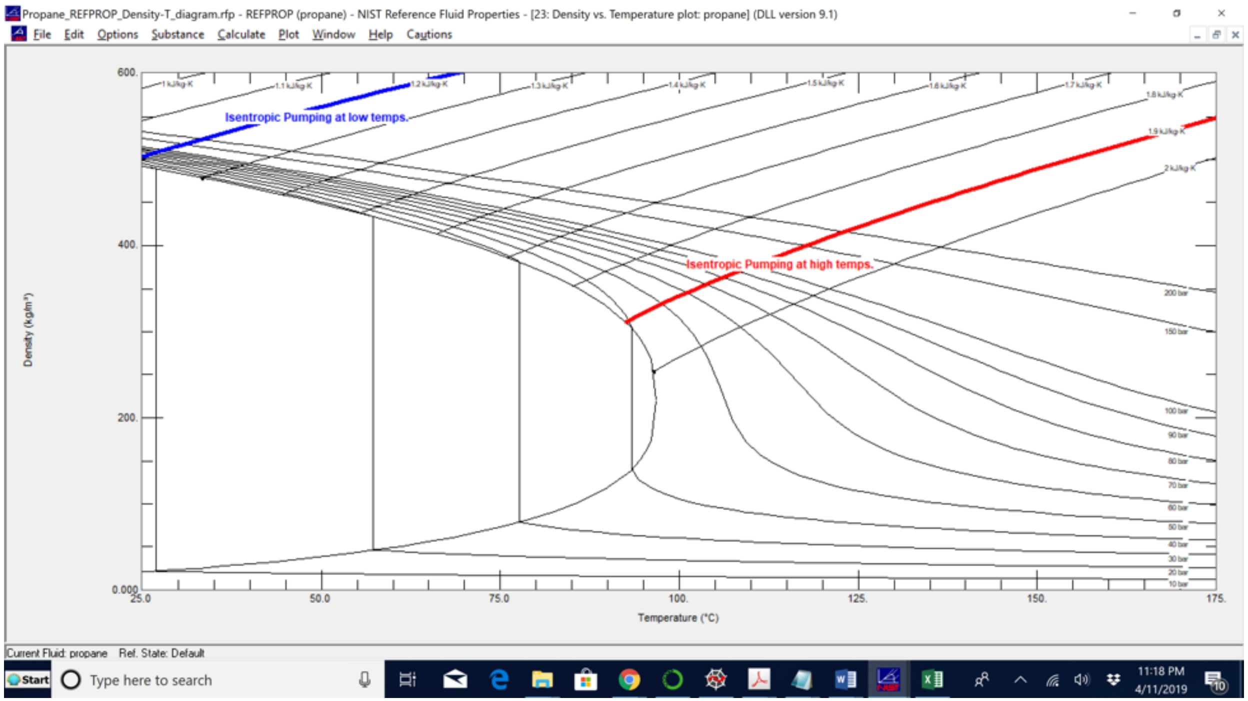
IMEP: Indicated mean effective pressure
RPM: Revolutions per minute
s: Seconds



- University of Alabama instrumented the 4.3L high pressure fuel system to collect dynamic response data under steady state and transient engine conditions.
- A 1-dimensional (1-D) GT-SUITE model was developed to evaluate fluid property change effects for propane versus gasoline, guiding hardware and calibration changes required to enable propane operation with existing injectors.

Technical Accomplishments and Progress

High pressure DI system dynamics for gasoline mapped and propane performance modeled



- University of Alabama studies on fuel system dynamics are critical to understanding propane phase changes and thermodynamic conditions existing in the vehicle tank, the low pressure pump, the high pressure pump, the fuel rails, and the direct injectors.
- Since Tier 1 suppliers do not yet see a market for unique propane DI injectors, production gasoline DI injectors must be adapted with control system changes to enable their use.
- Unlike DI gasoline, conditions during shut-down, cold-start, hot soak, and hot-restart may allow propane to become two-phase in the fuel system, leading to a loss of engine control.

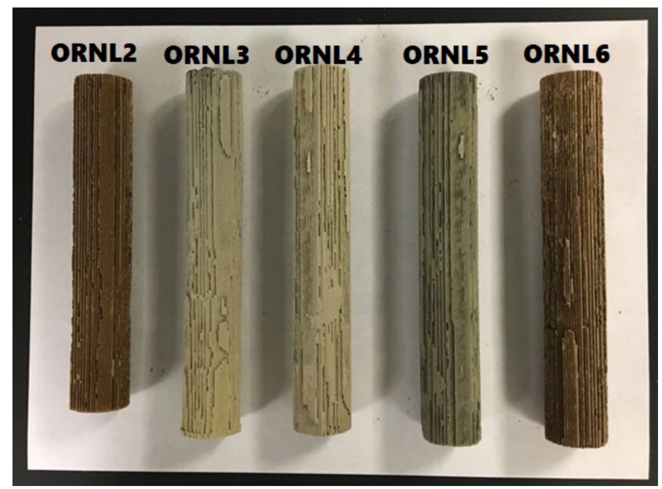
Technical Accomplishments and Progress

Range of three way catalysts (TWC) synthesized to evaluate low temp. propane conversion

Catalyst Matrix [OSC=oxygen storage capacity; NSC=NOx storage capacity]

sample ID	Description	Pt (g/l)	Pd (g/l)	Rh (g/l)	OSC	NSC
ORNL-2	$Pd_{6.36}$+$Rh_{0.14}$ w/o OSC	0	6.36	0.14	N	N
ORNL-6	$Pd_{6.5}$ w/o OSC	0	6.50	0	N	N
ORNL-5	$Pd_{6.5}$ with High OSC	0	6.50	0	H	N
ORNL-4	$Pd_{4.06}$ with Medium OSC	0	4.06	0	M	N
ORNL-3	$Pd_{1.41}$ with Low OSC	0	1.41	0	L	N

- Propane conversion at low temperatures is required to enable mono-fuel propane DI operation, without a “crutch” of using bi-fuel with gasoline for the challenging cold start.
- ORNL has conducted bench-scale flow reactor studies of new catalyst materials, in collaboration with Umicore.
  - Range of metals and functionalities included to find most reactive formulation at low temperatures

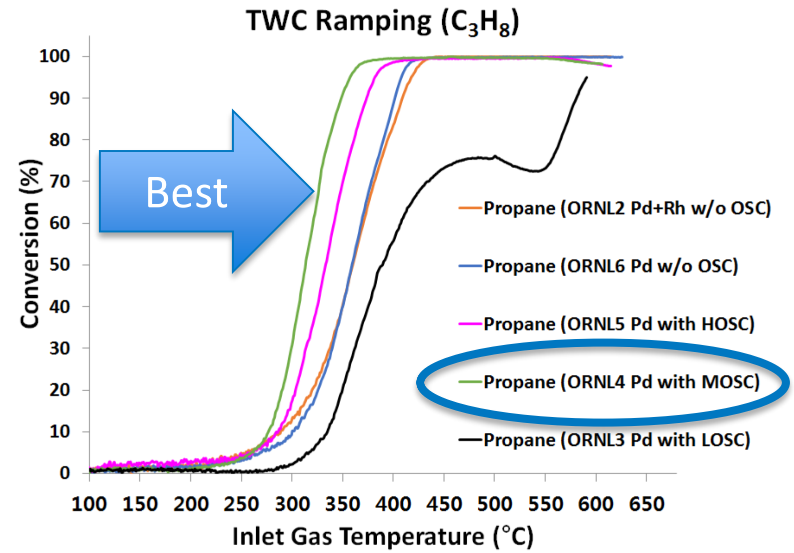


g: Gram
L: Liter
Pd: Palladium
Pt: Platinum
Rh: Rhodium

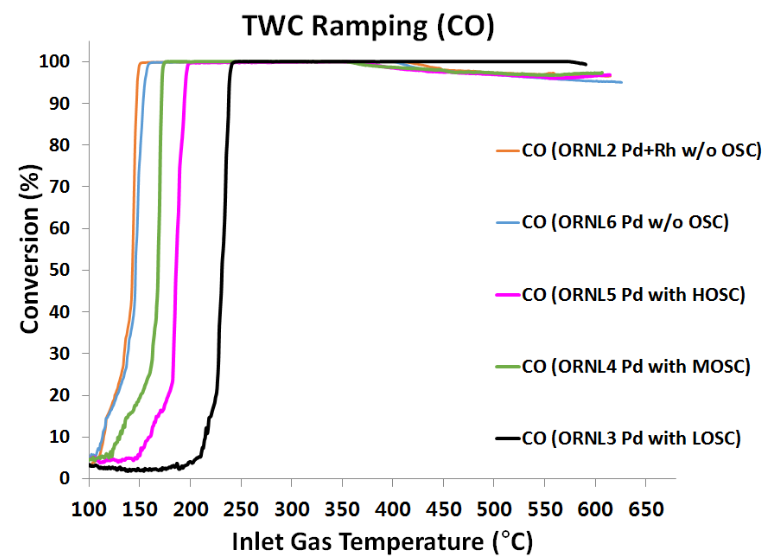
Technical Accomplishments and Progress

Initial results indicate Pd-Only with a mid-level OSC loading yields best propane reactivity

- Initial evaluations performed after degreening catalyst cores
- Stoichiometric evaluation performed with propane as the only hydrocarbon
  - Can modify based on engine evaluation findings
- Catalyst with mid-level OSC (oxygen storage capacity) showed the best reactivity for propane
- CO reactivity trends are show best reactivity without any OSC
  - TWC w/ mid-level OSC is best when OSC is present



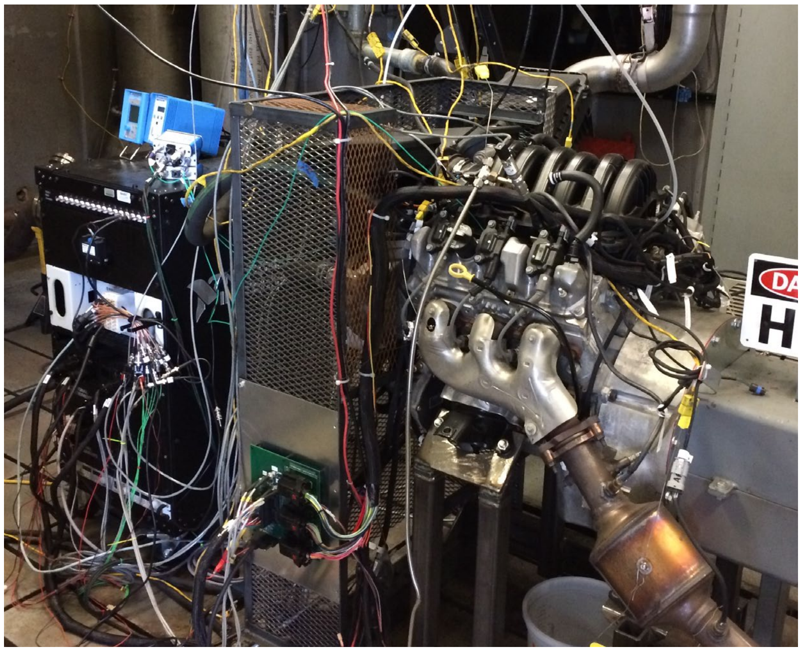
Gas	Concentration
C_3H_8	1000 ppm
CO	5000 ppm
NO	1000 ppm
O_2	0.78% (stoichiometric)
H_2	1670 ppm
H_2O	13%
CO_2	13%
N_2	Balance
GHSV	60,000 h^{-1}

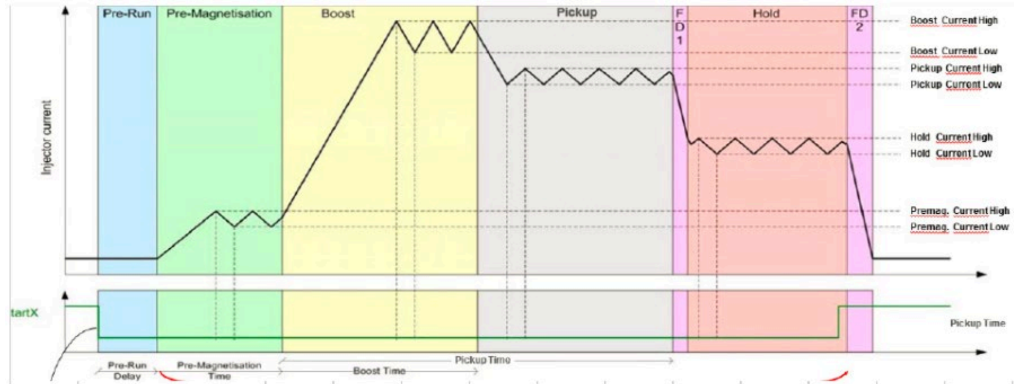


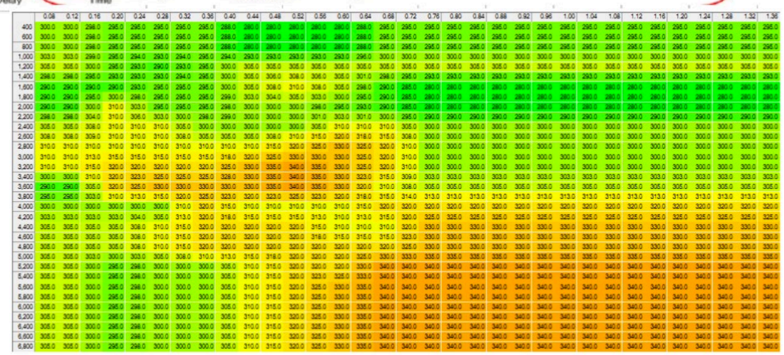
C3H8: Propane
CO: Carbon monoxide
CO2: Carbon dioxide
H2: Hydrogen
H2O: Water
O2: Oxygen
N2: Nitrogen
NO: Nitric oxide
GHSV: Gas hourly space velocity

Technical Accomplishments and Progress

Mapped baseline 4.3L DI gasoline controls from which to develop propane-specific controls







- NREL and Vieletech extensively mapped the 4.3L with Chevrolet Silverado production controls on a chassis dynamometer, then transitioned to engine dynamometer studies on gasoline with independent controls.
- Operation with production hardware provided a starting point from which to develop propane-specific controls and calibration, guided by U. Alabama’s fuel system simulations.
- Conversion to propane operation is underway, and will include integration of a “vehicle-like” propane storage / low pressure pump system to address key technical barriers.

Responses to Previous Year Reviewers' Comments

This project has not previously been reviewed at a VTO Annual Merit Review.

Collaboration and Coordination

- **NREL**
  - Conducting 4.3L engine systems research for DI propane, including chassis and engine dynamometer experimental studies
- **ORNL**
  - Conducting emissions controls research, including catalyst materials evaluations and particulate matter studies
  - Including a graduate student (Dae-Kun Kim) for thesis research through the University of Tennessee (Prof. Ke Nguyen)
- **University of Alabama**
  - Conducting experimental studies at NREL (including sending a Ph.D. student to NREL during summer of 2018)
  - Building 1-D high pressure fuel system simulations, and combustion simulations
  - Sponsoring two graduate students with this research
- **Vieletech**
  - Under subcontract to NREL, with deep expertise in developing independent engine controls (Dr. Matt Viele, Drivven founder)

Collaboration and Coordination

- **Blossman Services**
  - Project PI for and prime for former FOA award (under NETL subcontract)
  - Continues to provide technical guidance, propane fuel system design (vehicle side), and collaboration
- **Freightliner**
  - Provided technical guidance, vehicle specifications, and performed vehicle simulations for go/no-go decision
- **United Parcel Service**
  - Provided technical guidance
  - Supplied package delivery truck used in NREL chassis dynamometer studies
  - Planned to operate prototype vehicle in fleet operation testing
- **Umicore**
  - Collaborating with ORNL to provide low-temperature, propane-active catalysts
- **U. S. Environmental Protection Agency**
  - Providing technical exchange
  - Shared 4.3L engine mapping data from prior EPA research study

Remaining Challenges and Barriers

- While the project shifted away from the FOA award scope due to commercialization drivers, the revised project focuses on remaining key technical challenges and barriers for propane to adopt direct injection.
- Project focus is now on **deeper dive into dynamic high pressure fuel system performance** under steady state and transient engine operation
  - Transition to gas-phase within the fuel system is a major issue
  - Propane thermodynamic properties differ significantly from gasoline, and one must account for those to use gasoline direct injectors (no propane specific injectors until industry builds sufficient volume).
- Project focus also continues to include **emissions controls and catalyst materials that enable low temperature propane conversion** – key industry segments prefer mono-fuel.
- The revised project focuses on earlier stage research with publication emphasis to inform industry for subsequent commercial development.

Proposed Future Research

For the remainder of this funded project:

- Finalize milestones (with DOE concurrence) for continuation of re-scoped project.
- Equip NREL's engine dynamometer with vehicle-representative propane fuel system to continue 4.3L propane-specific controls research.
- Link University of Alabama's fuel system and combustion system simulations to drive propane-specific controls.
- Continue bench-scale catalyst materials development, then scale up to couple catalyst to NREL's engine dynamometer.
- Collect particulate matter emissions as industry guidance for DI effects with propane.
- Link all of the above to develop propane-specific controls to provide (and publish!) industry guidance on how DI propane barriers can be addressed through hardware and controls changes.

With additional funding, proposed future research*:

- While this specific engine ultimately faced commercialization challenges, industry collaboration could leverage this project as early-stage development to support another engine platform.
- The propane industry has been asking for comparative fuel economy / emissions studies versus baseline (gasoline or diesel) to inform Autonomie. We have a baseline gasoline dataset already for a key Class 5/6 application from this study, and could study a current technology PFI propane variant.

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

Summary

- This project began as a FOA award project to conduct research and development for adapting a General Motors 4.3L SIDI gasoline engine to mono-fuel propane DI operation.
- Focus was on controls and aftertreatment development with minimum other hardware changes that would preclude post-project commercialization.
- While the vehicle integration, certification-ability demonstration, and fleet use testing are no longer in scope, the remaining project still focuses on key industry challenges:
  - Developing controls hardware, strategy, and calibration to enable DI propane based on gasoline DI platforms
  - Developing aftertreatment with low temperature conversion to support mono-fuel DI propane engines.

The project team members wish to thank Dr. Michael Weismiller and DOE Vehicle Technologies Office for support of this research.

Thank You

www.nrel.gov

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