Evaluation of the Fuel Economy Impacts of Low Temperature Combustion (LTC) using Engine-in-the-Loop

2013 DOE Hydrogen Program and Vehicle Technologies Annual Merit Review

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Neeraj Shidore (PI) – Vehicle Systems
Stephen Ciatti– Engine and Emissions Research
Argonne National Laboratory

Sponsored by David Anderson, Gurpreet Singh

Project ID # VSS111

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Project Overview

Timeline	Barriers
Start Date: September 2012 End Date: September 2013 Percent Complete: 30%	• Development and robust control of LTC combustion process over different operating points.
Budget	**Partners**
Total Project Funding • DOE, Vehicle Systems: $100 K • DOE, Advanced Combustion: $100 K	• Dr. Stephen Ciatti, Engine and Emissions Research ,ANL.

Research Objective

Evaluate the Fuel Economy Impact of Low Temperature Combustion (LTC) Technology using Engine-in -the Loop

- Quantify the fuel economy benefit of LTC Engine on standard drive cycles using Engine-in-the-Loop.
- Evaluate the test-to-test variability with LTC combustion compared to diesel.
- Evaluate transient behavior through Engine-in-the Loop.
- Compare the fuel economy of the LTC technology with PFI and SIDI engines though simulation.

Relevance

- Low temperature combustion research is being conducted by DOE to improve the efficiency of engines for light duty passenger vehicles‡ .

Gurpreet Singh, Team Lead, Advanced Combustion Engines, Department of Energy Merit Review, 2012

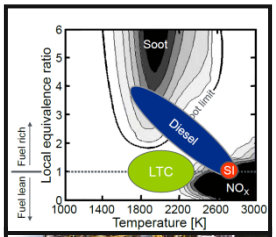
- One of the goals of vehicle systems research at DOE is to rapidly evaluate components and systems though model based design and hardware in the Loop†.

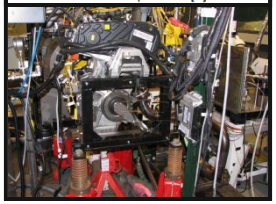
† http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/vt_mypp_2011-2015.pdf: Vehicles System and Simulation.
‡ http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/vt_mypp_2011-2015.pdf: Advanced Combustion Engine R&D.

Approach: Leverage Existing Expertise in Vehicle System Simulation, Component-in-the-loop and LTC Engine Research.

Existing vehicle Simulation models

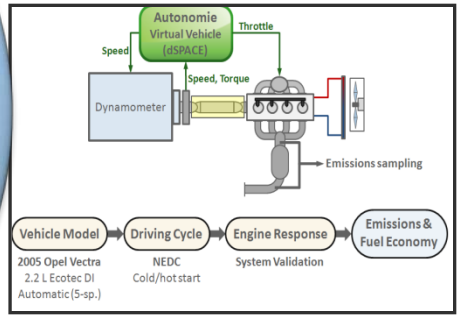
Existing Expertise in LTC Combustion in a TDI Engine



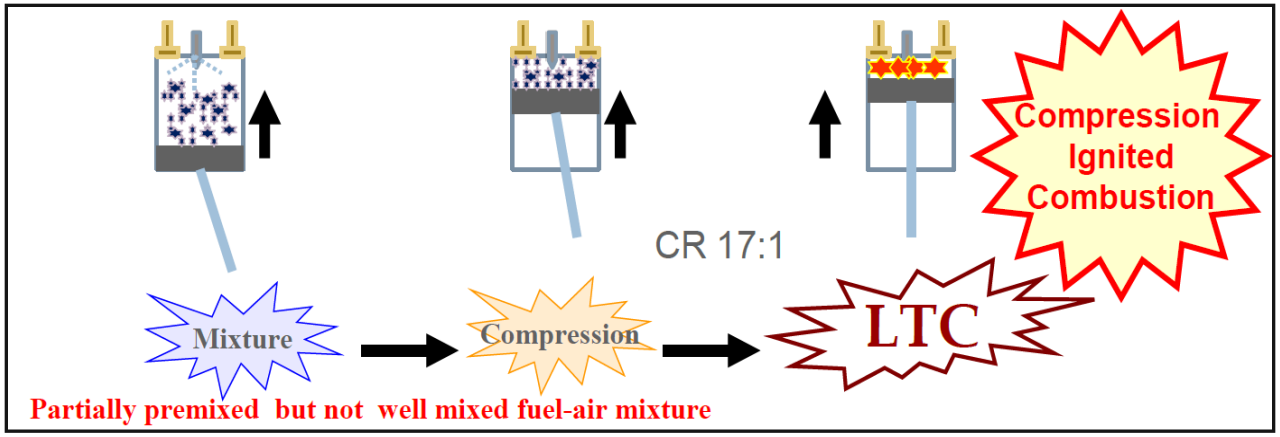


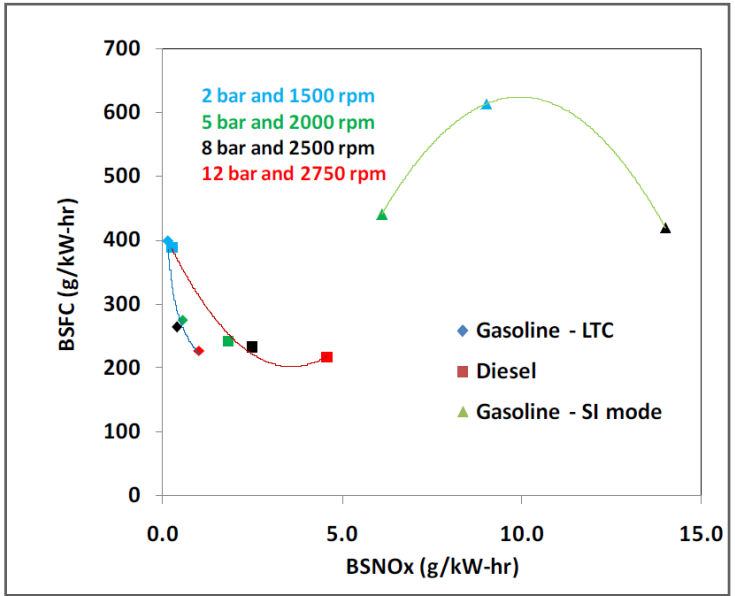
Quantify the fuel consumption benefits of LTC over SIDI and PFI for a conventional powertrain.

Existing experience in Engine in the Loop



Approach: Leverage LTC Research at Argonne National Laboratory





Color of marker: Operating point.
Color of trend line: fuel.

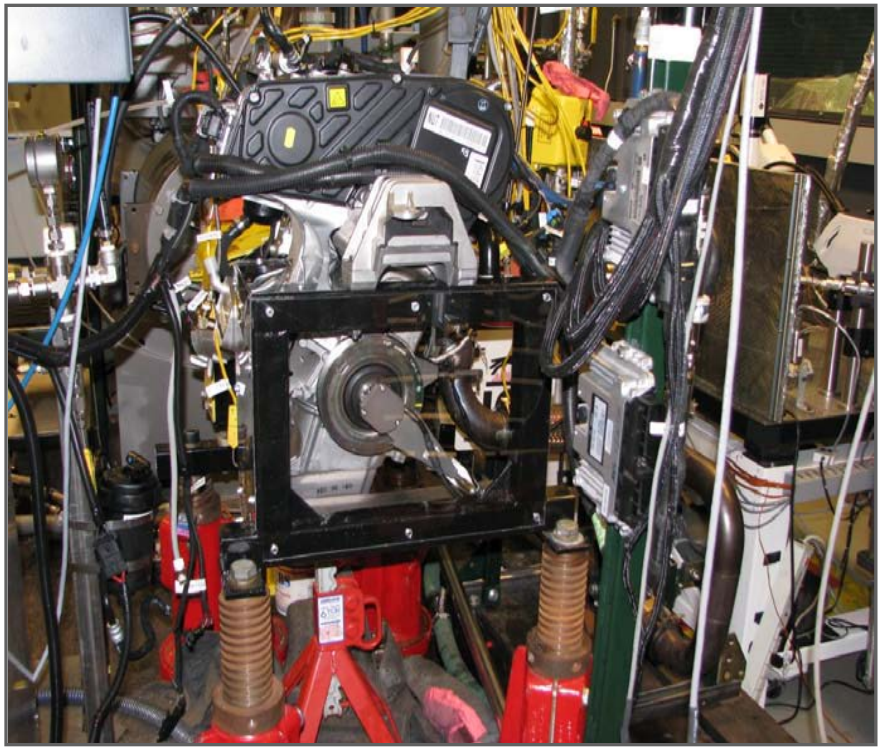
- LTC combustion shows lower fuel consumption and NOx when compared to Gasoline SI.
- Detailed Presentation (ACEO11): Stephen Ciatti: Use of Low Cetane Fuel to Enable Low Temperature Combustion (Tuesday, May 14th).
- All pictures from Stephen Ciatti, et al, 'An Experimental Investigation of Low Octane Gasoline in Diesel Engines' presented at DEER 2010.

LTC Technology being Evaluated on a GM 1.9 L TDI Engine.

Property	Default fuel for the engine – # 2 diesel	Fuel under investigation for LTC – Low octane gasoline
Specific gravity	0.8452	0.7512
Low heating value (MJ/kg)	42.9	42.5

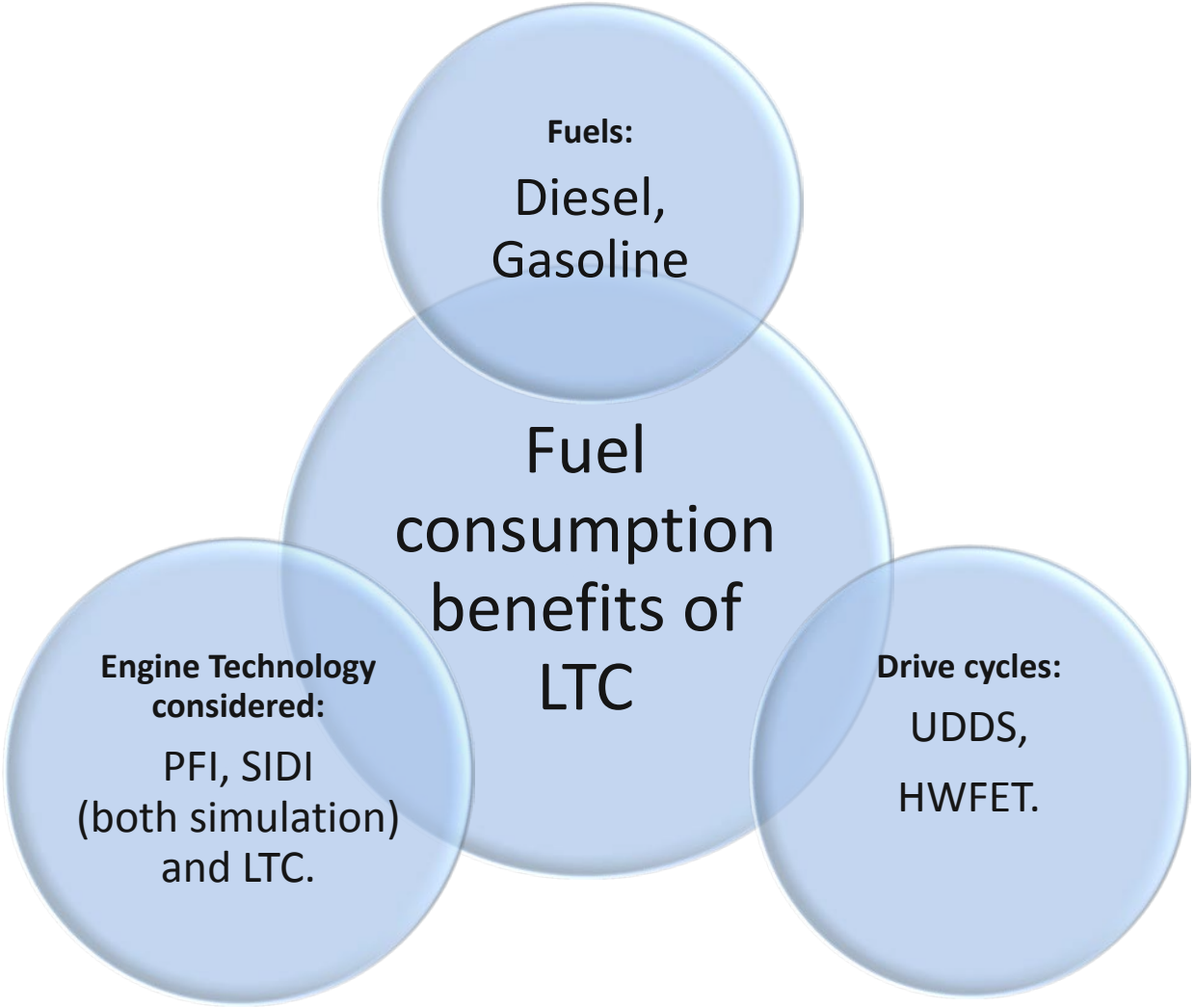
Production vehicle with the engine:
2007 Cadillac BLS Wagon (Europe).

GM 1.9 L TDI Engine, 110 kW peak at 4500 RPM.



Picture and data from : S. Ciatti, S. Subramaninan, 'An Experimental Investigation of Low Octane Gasoline in Diesel Engines', presented at DEER 2010, Dearborn, MI, September 29th, 2010.

Approach - Design of Experiment



Conventional midsize vehicle with manual transmission considered for the experiment.

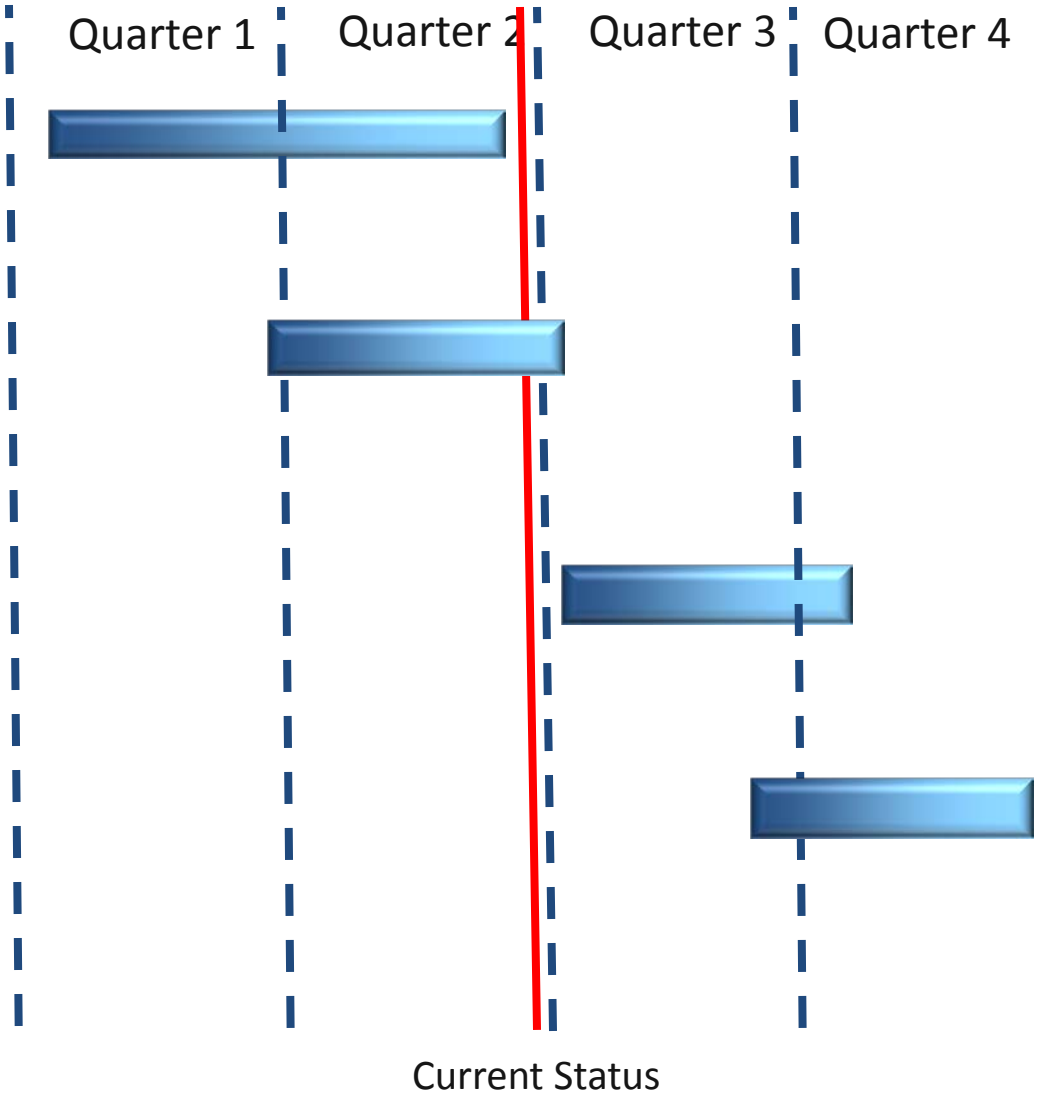
Milestones

Simulation study to quantify the fuel economy benefits of LTC combustion.

Implementing engine in the Loop with the 1.9 L TDI engine.

EIL testing with diesel fuel.

EIL testing with gasoline fuel.



Technical Accomplishments

Vehicle Fuel Consumption Correlated with Published Data

Vehicle	Cadillac BLS Wagon
Vehicle Mass	1560 kg
Engine*	1.9L TDI , 110 kW, 320 Nm peak torque, I-4.
Transmission	Manual , 6 speed.

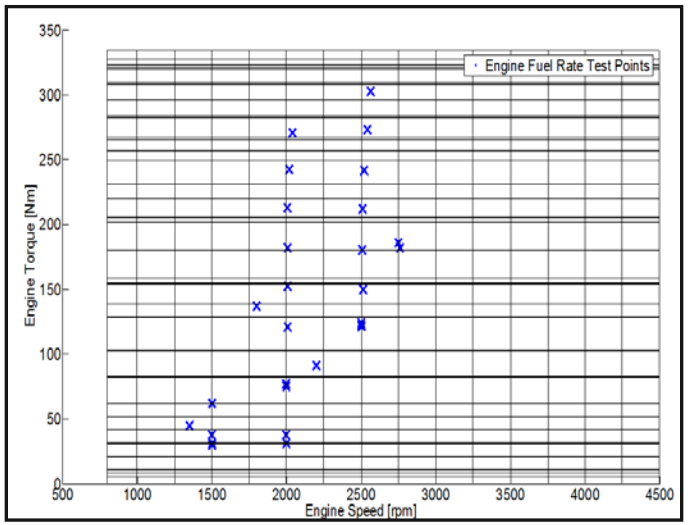
	Simulation	**Test****
Fuel Consumption (NEDC – Extra Urban)	4.9 L/100 km	4.8 L/100 km
IVM-100 km/h	9.6 seconds	9.6 seconds

* Same engine to be used for the HIL study. Simulation co-relation used the steady state map with diesel fuel.

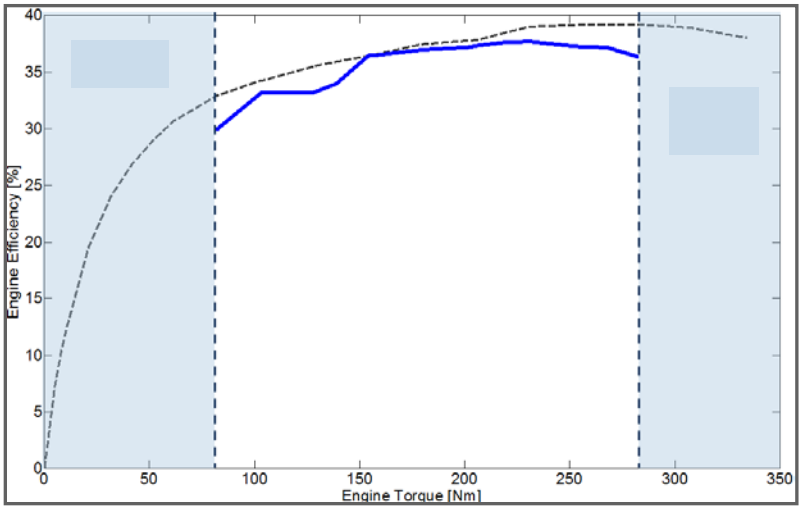
** http://www.carinf.com/en/9220414062.html.

Technical Accomplishments

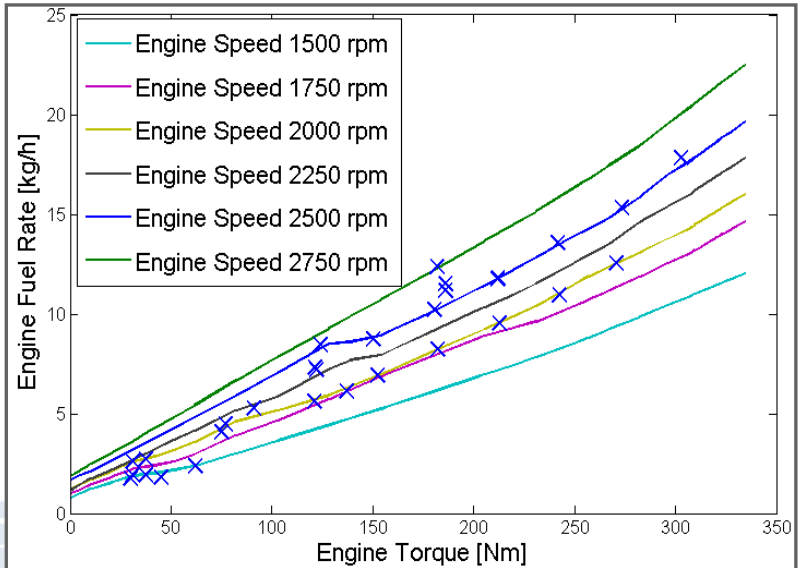
Engine Efficiency Map Generated from Limited Data Points for LTC (gasoline).



Limited Engine test data for the LTC of gasoline in the 1.9 L Engine.



Efficiency curve for 2500 rpm data points

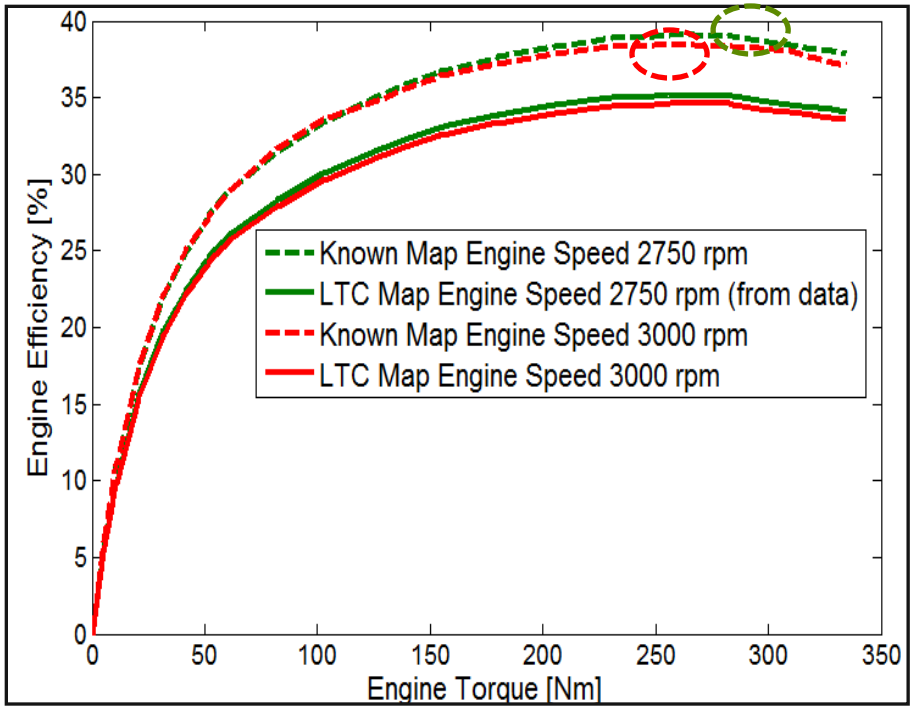


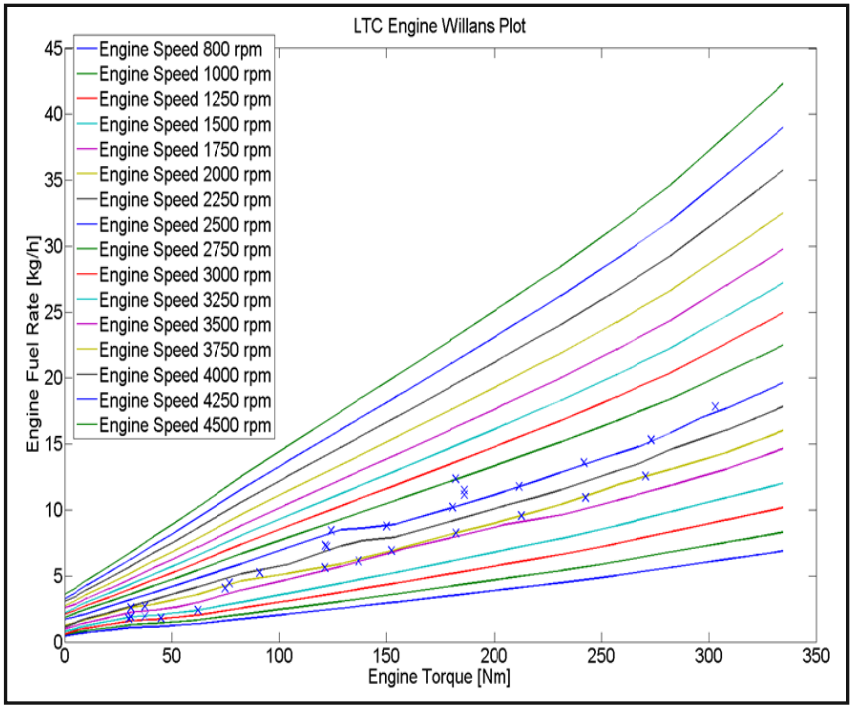
Willans lines for available engine data

Technical Accomplishments

Map Completed by Creating Efficiency Lines Proportional to Available Efficiency Curves (from data)

$$\eta_{LTC,3000\ RPM}(T1) = \frac{\eta_{known,\ complete\ map,\ max}(3000\ rpm)}{\eta_{known\ complete\ map,\ max}(2750\ rpm)} \times \eta_{LTC,2750}(T1)$$

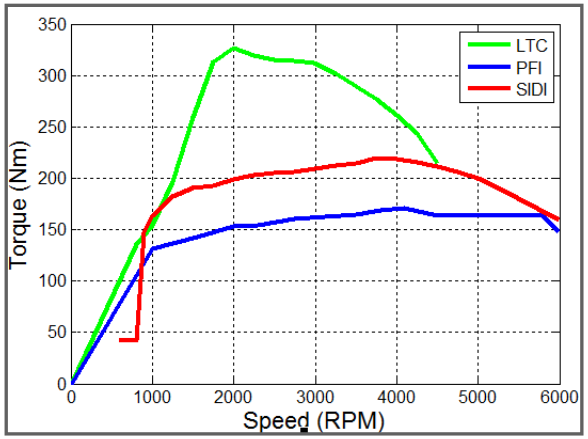




Willans lines for completed map for LTC combustion.

Technical Accomplishments

Engine Power Scaled for the SIDI and PFI Technologies to Match Vehicle Specification with LTC Gasoline.



Peak Torque curves for the un-sized PFI, SIDI engines and the LTC engine.

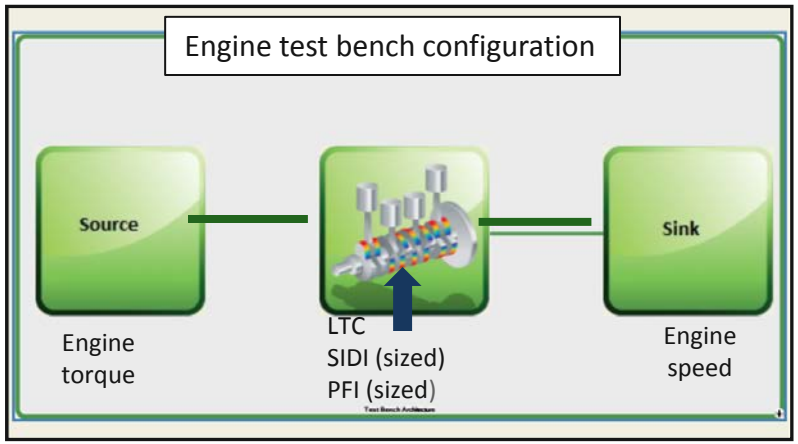
Max torque of LTC gasoline is similar to Diesel.

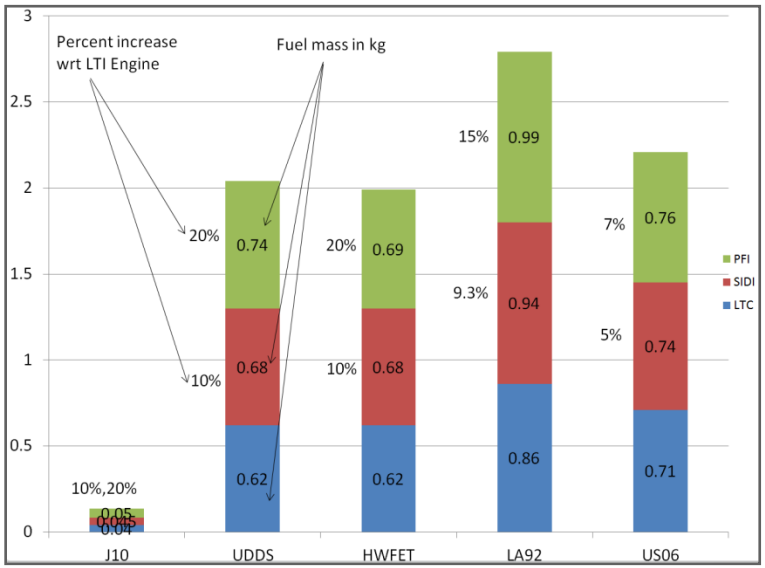
Target performance: IVM -100 km/hr in 9.6 seconds (Cadillac BLS Wagon with a diesel engine).

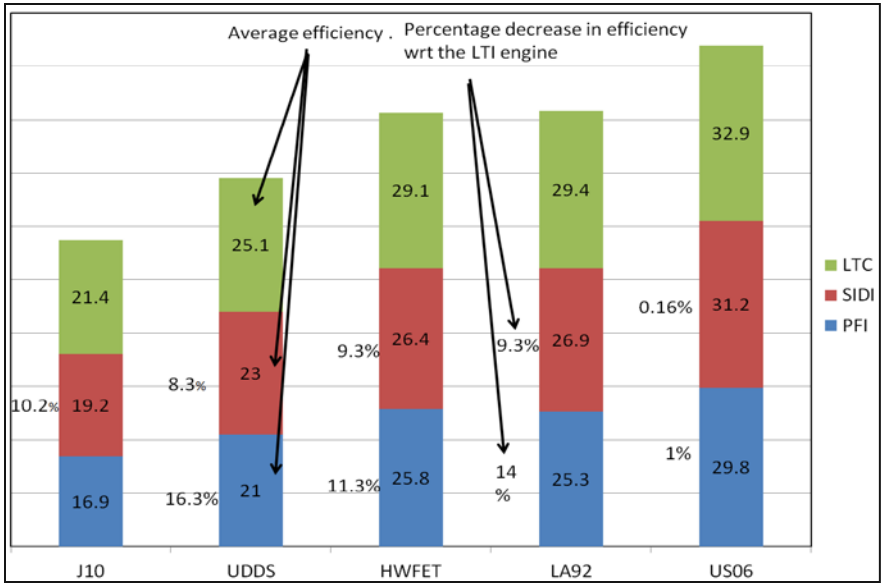
Fuel / Combustion Technology	Engine Scaled Power to meet IVM-100 km/hr in 9.6 seconds
Diesel	110 kW
Gasoline with LTC	115 kW
Gasoline with SIDI	135 kW
Gasoline with PFI	147 kW

Technical Accomplishment

Fuel Economy Gains with Identical Engine Speed and Torque Profile Quantified in Simulation







Engine speed and torque profile based on the Cadillac BLS Wagon gear-ratios and final drive.

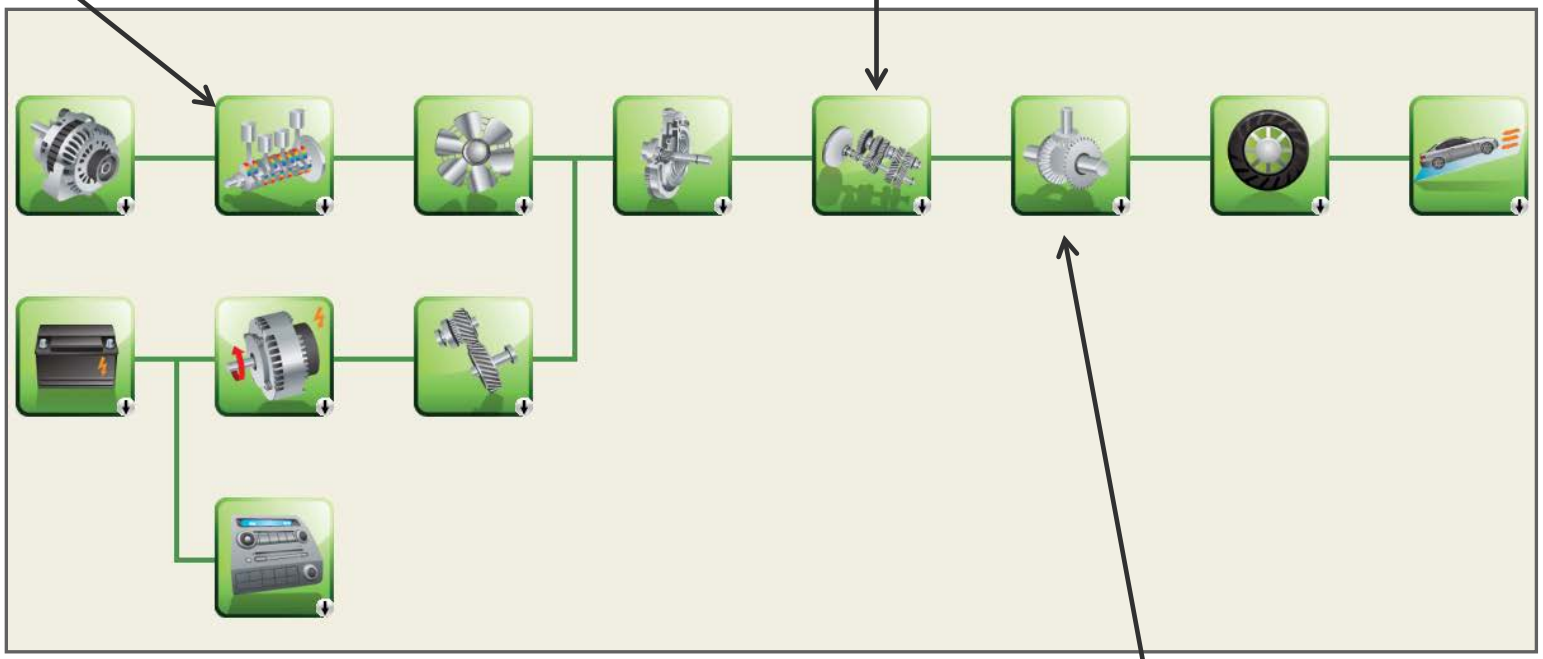
Technical Accomplishments

Simulation Comparison between LTC, SIDI and PFI Technologies.

PFI (1.8 L Peugeot)
SIDI (2.2 L ECOTEC GM)
LTC (from generated map)

Transmission ratios

SIDI , PFI	4.16	2.20	1.48	1.15	0.92	0.74	GM F40 for the ECOTEC family
LTC	3.77	2.04	1.37	1.05	0.85	0.71	Ratios for the Cadillac BLS.



Final drive ratios
SIDI,PFI: 4.43 - GM F40.
LTC: 3.55 – Ratio for the Cadillac BLS.

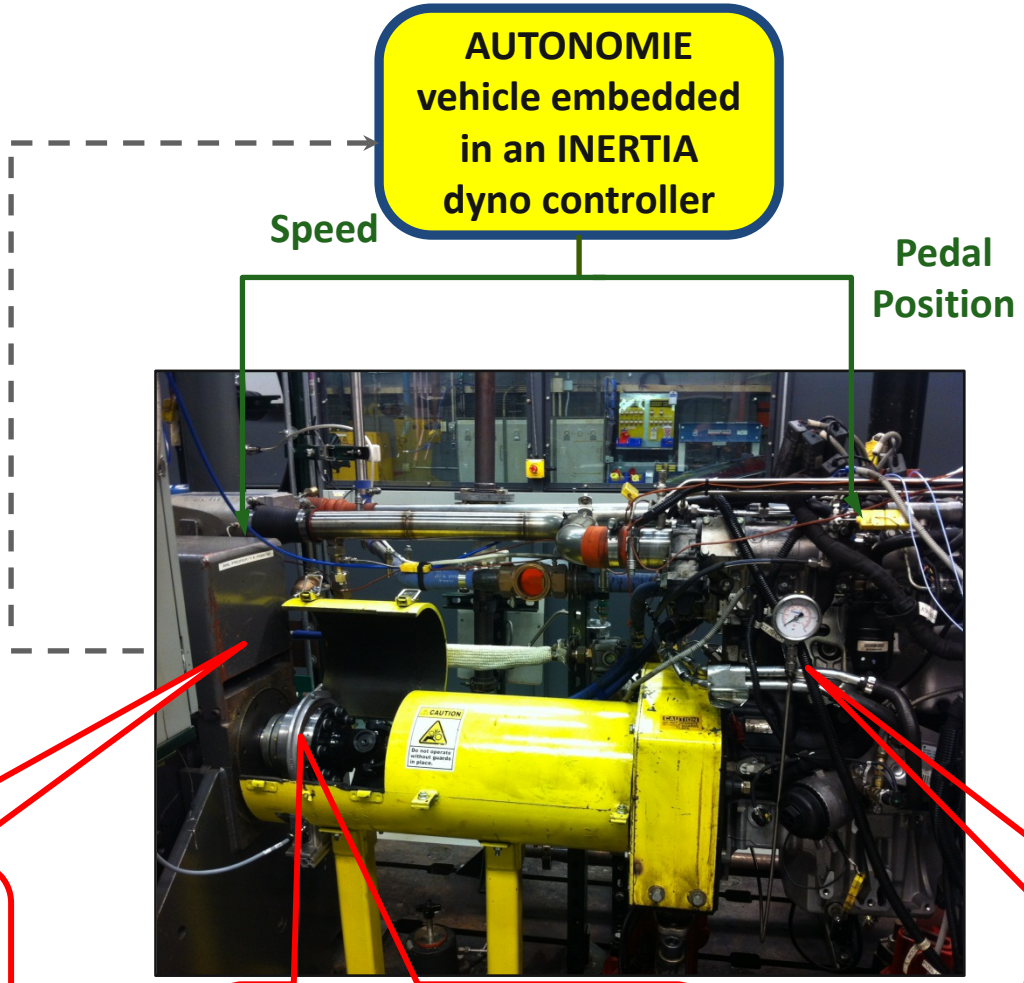
Technical Accomplishments

LTC Combustion Shows Significant Fuel Economy Improvement over PFI and DI

Fuel Economy [mpg, unadjusted]	PFI	SIDI	LTC
UDDS	26.3	30.4	32
HWFET	33.2	41.5	45.3
Combined[55/45]	29	34.6	37
Improvement over PFI		16%	26%
Improvement over SIDI			7%

Technical Accomplishment

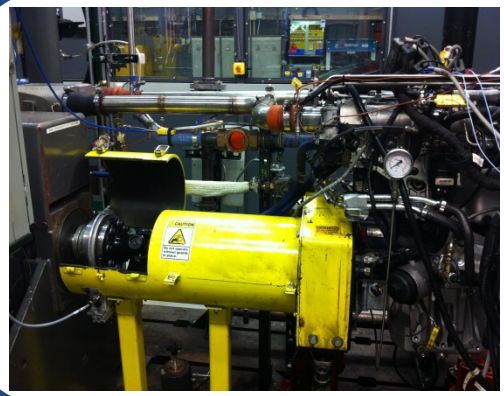
Hardware Modifications for Engine in the Loop Underway.



Collaboration and Co-ordination with other institutions

Engine and Emissions group at ANL
Dr. Stephen Ciatti, LTC combustion research

GM R&D, technical support with the 1.9 L TDI Engine



DOE technology evaluation
- DOE requests
- National Lab requests

NREL ornl INL Argonne

AUTONOMIE
Virtual vehicle model

AUTONOMIE

USDrive, tech teams and OEMs
Share test plans, data and analysis

USDRIVE

Future Work

On going work for FY13

- Complete modification of engine test cell for Engine in the Loop.
- EIL testing with diesel fuel – quantify engine out emissions and fuel consumption.
- EIL testing with gasoline using LTC technology – quantify emissions and fuel consumption.

Potential follow-up

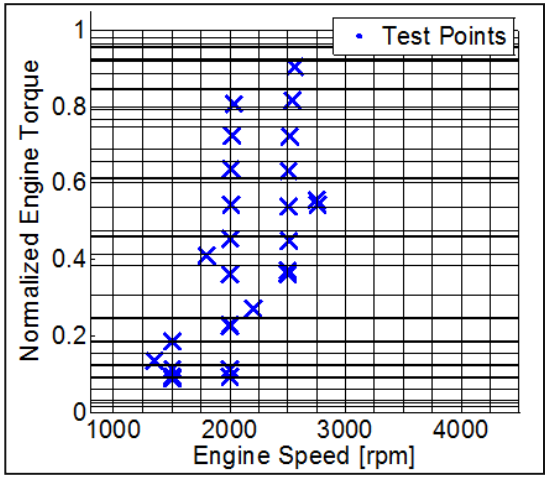
- Compare engine-out emissions between LTC gasoline (current experiment) and SIDI combustion from previous study.
- Evaluate the impact of hybridization on fuel economy gains due to LTC gasoline compared to SIDI and PFI.

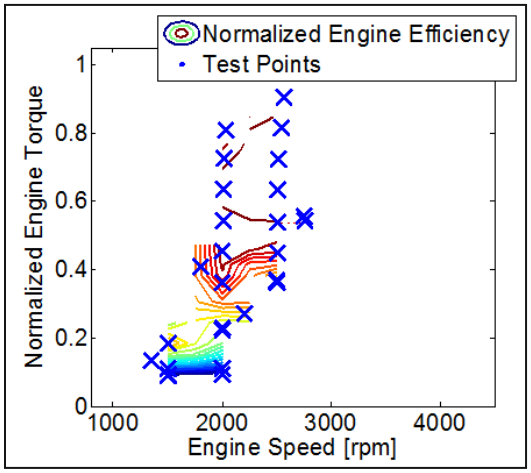
Summary

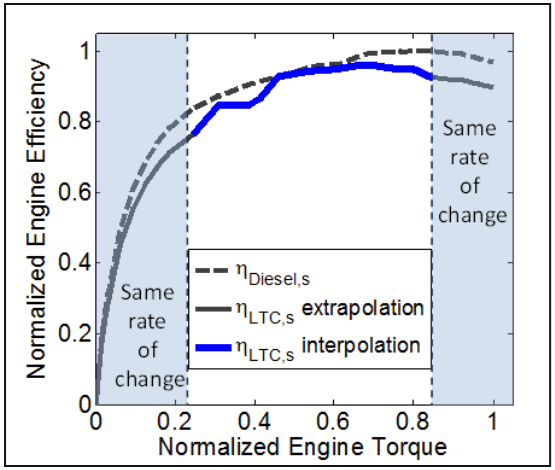
- Several existing capabilities have been leveraged to compare the fuel consumption potential of low temperature gasoline combustion to SIDI and PFI technologies
  - Engine and emissions research on LTC.
  - Engine-in-the-loop capabilities with AUTONOMIE.
  - AUTONOMIE simulation capabilities.
- A process was developed to generate a complete engine map from few selected test data points, in order to compare LTC to SIDI and PFI by simulation.
- Simulation of LTC and comparison with PFI & SIDI show significant improvements in fuel economy.
- Engine-in-the-Loop will be used to validate the fuel consumption benefits from the simulation as well as quantify the engine out emissions.

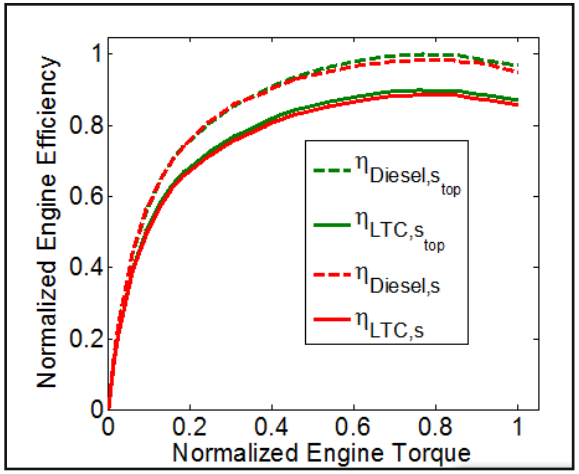
Technical Back-Up Slides

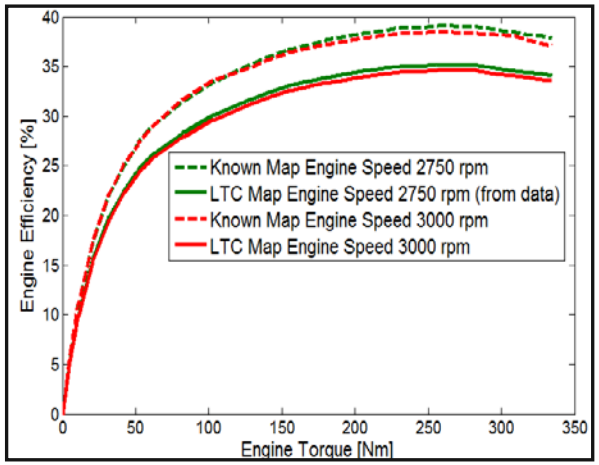
Engine efficiency map generation



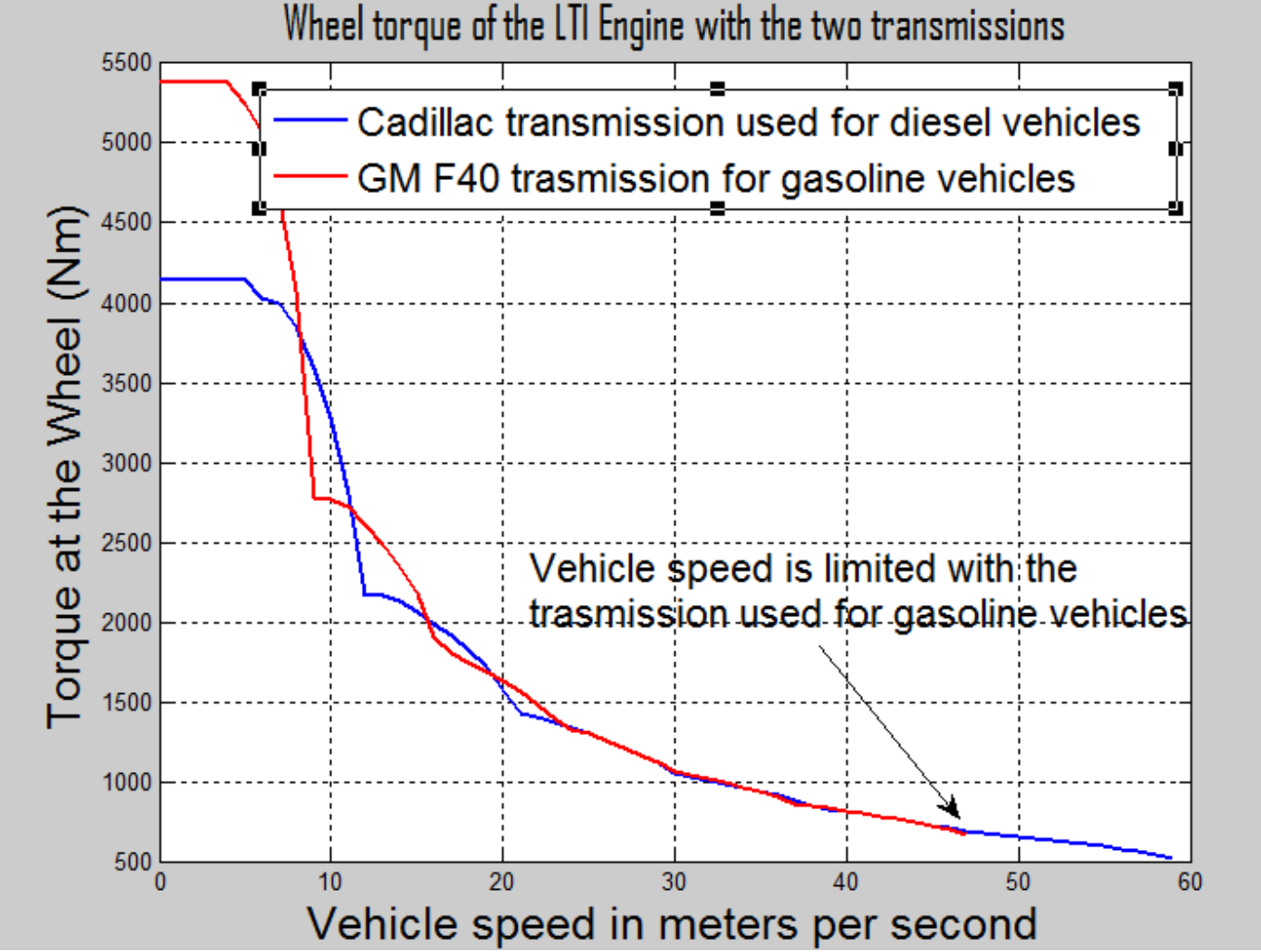








Need for a different transmission for the LTI Engine.



Impact of sizing – increased tractive effort with increase in engine power.