High Compression Ratio Turbo Gasoline Engine Operation Using Alcohol Enhancement

PI: John B. Heywood
Sloan Automotive Laboratory
Massachusetts Institute of Technology

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Project ID FT016

Overview

Timeline

- Project start date: 9/01/2011
- Project end date: 1/15/2015 (with no-cost extension)
- Percent complete: 77%

Budget

- Total project funding:$1,203,122
  - DOE share: $962,497
  - Contractor share: $240,625
- Funding received in FY13: $168,748
- Funding for FY14: $167,337

Barriers

- Barriers addressed
  - Peak thermal efficiency (LDV) > 45%
  - Peak fuel efficiency improvement (LDV) > 25%
  - Emission control fuel penalty < 1%

Partners

- Cummins Inc
- Project lead: MIT

Relevance/Objectives

- Objectives:
  - To explore and assess the potential for higher efficiency gasoline engines through use of non-petroleum fuel components that remove existing constraints on such engines while meeting future emissions standards
  - Investigate the benefits of knock-free SI engines through the use of alcohol blending with gasoline
  - Substantially improve efficiency through raising the compression ratio, increasing boost (in turbocharged engines), and engine downsizing, enabled by knock-resisting properties of alcohols
- FY13-14 goals
  - Experiments and simulations to demonstrate thermal efficiency improvement of > 25% over drive cycle for LDV
  - Determine means of decreasing use of high octane fuel

Approach/Strategy

- Approach: Ethanol's unique properties as a SI fuel:
  - High octane of ethanol can be used to avoid knock at high load
    - Evaporative and chemical octane components important
  - At part loads, lower octane gasoline used, minimizing the amount of high octane fuel used through a driving cycle
- Strategy: Combination of engine tests, engine and vehicle simulations, to quantify potential of approach
  - Dyno-engine testing with gasoline and alcohol fuels
  - Tests carried out in TC engine at MIT, and in a stronger MDV engine at Cummins using different fuel compositions
  - Simulations using combustion (Chemkin), engine (GT-Power) and vehicle (Autonomie) models

Project Milestones - 1

Phase 1-2

	Phase 1. Technology Design			
Feb 2012	Engine modifications	M	Modify engine for DI of ethanol/gasoline blends	Completed
May 2012	Engine test matrix	M	DOE with fuels (ethanol+gasoline, ethanol+gasoline+water methanol+gasoline, torque, speed	Completed
Aug 2012	Initial engine test	G	Tests at various speeds and torques in LDV engine with ethanol/gasoline blends	Completed
	Phase 2. Technology Development			
Dec 2012	Engine operating map development	M	Tests at various speeds and torques in LDV engine with ethanol+water+gasoline blends	Completed
Apr 2013	High pressure engine modification	M	Modification of diesel engine block with SI head at Cummins	Completed
Jun 2013	Low pressure engine simulation	M	Chemkin and GTPower models, benchmarlked to experimental results	Completed
Aug 2013	High pressure engine testing and Simulation	G	Worked carried out at Cummins in engine capable of high pressure operation	Completed

Project Milestones - 2

Phase 3

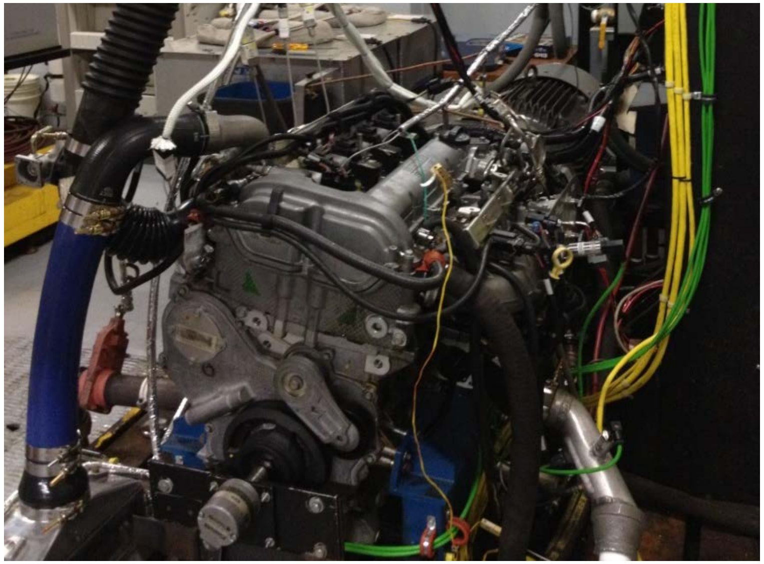
	Phase 3. Technology readiness			
Oct 2013	Engine and vehicle selection and simulations	M	Developed Autonomie model for Camry-like sedan	Completed
Feb 2014	Efficiency and alcohol use through driving cycles	M	Run model for several driving cycles with different compression ratios and downsizing/turbocharging	Completed
May 2014	Heavy duty vehicle simulation	M	Impact of technology on driving cycles for MDV and HDV	Ongoing
Aug 2014	Hydrous ethanol vehicle simulation	M	Cycle evaluation of hydrous ethanol as means of reducing cost of fuel and high octane fuel usage.	Ongoing
Dec 2014	Cost analysis	M	Additional cost of technology; cost of more sophisticaed engine/vehicle calibration; cost impact on Cost-of-Ownership of vehicle	Ongoing

Technical Accomplishments

Experimental / Simulation Approach

Experimental Engine –
GM Ecotec LNF

- DISI turbocharged
- Inline 4 cylinder
- 9.2:1 Compression Ratio
- Maximum boost: 2 bar abs. MAP



GT-Power Simulation

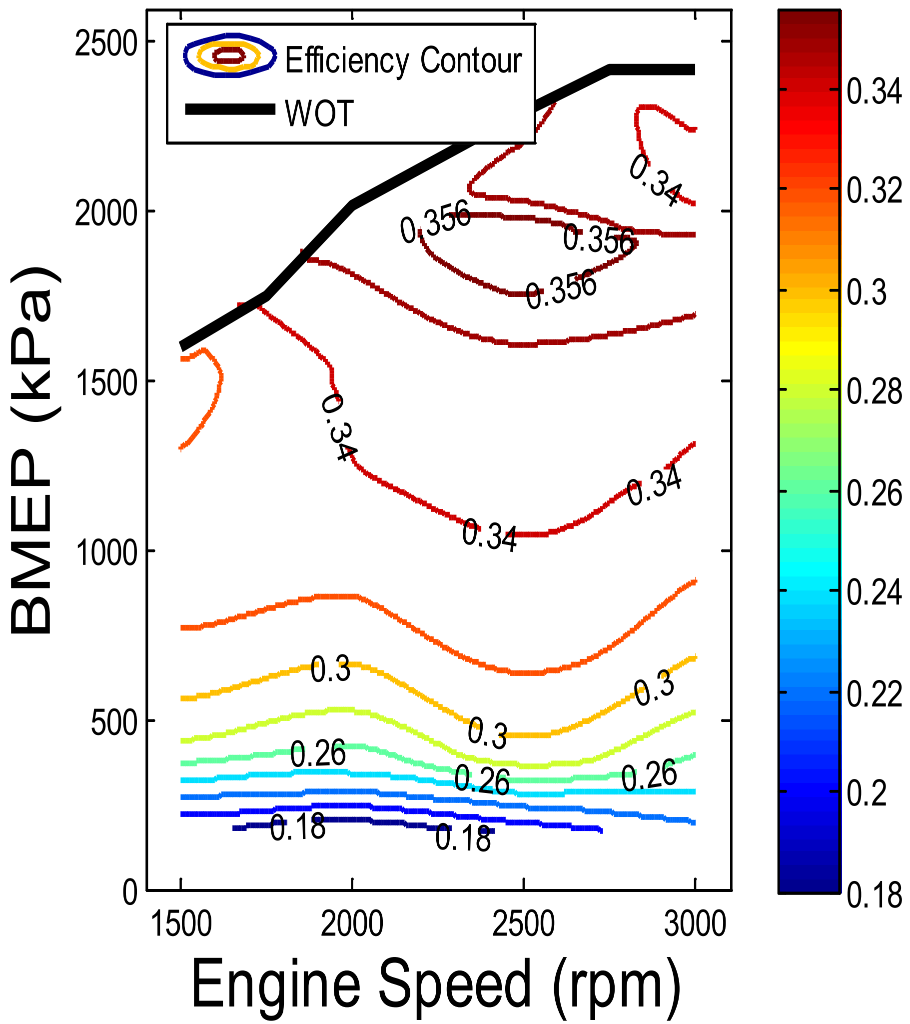
- Results beyond experimental limits and test constraints
  - Engine speed, boost level, compresison ratio, peak pressure
- Heat Transfer, charge cooling, and combustion efficiencies
  - Adjusted to match experimental results

Livengood-Wu Auto-Ignition Integral Model

- To predict knock onset using pressure and temperature from the simulation

Technical Accomplishments

Performance Map



Efficiency Contour

- Using knock resistant fuel (E85)
- At MBT timing except over the maximum pressure limits

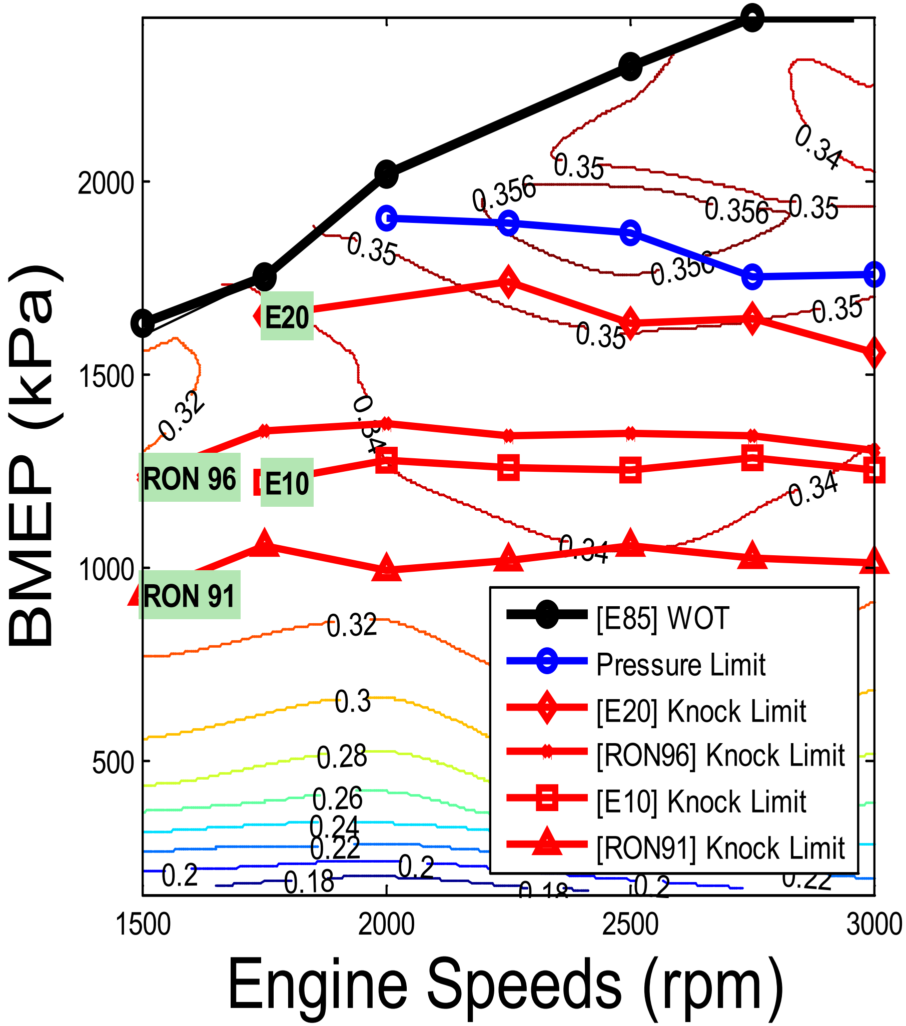
Efficiency

- Increases as the load increases, but there is a diminishing return
- Increase is relatively large at light load

Status: Experimental maps for the 2 liter TC engine for ethanol-gasoline blends, defining BSFC, efficiency, and WOT constraints completed

Technical Accomplishments

Operating Limits



Knock Limits

- RON 91 ~ 1000 kPa BMEP
- To reach above 1000 kPa BMEP, spark retard or higher RON fuels required

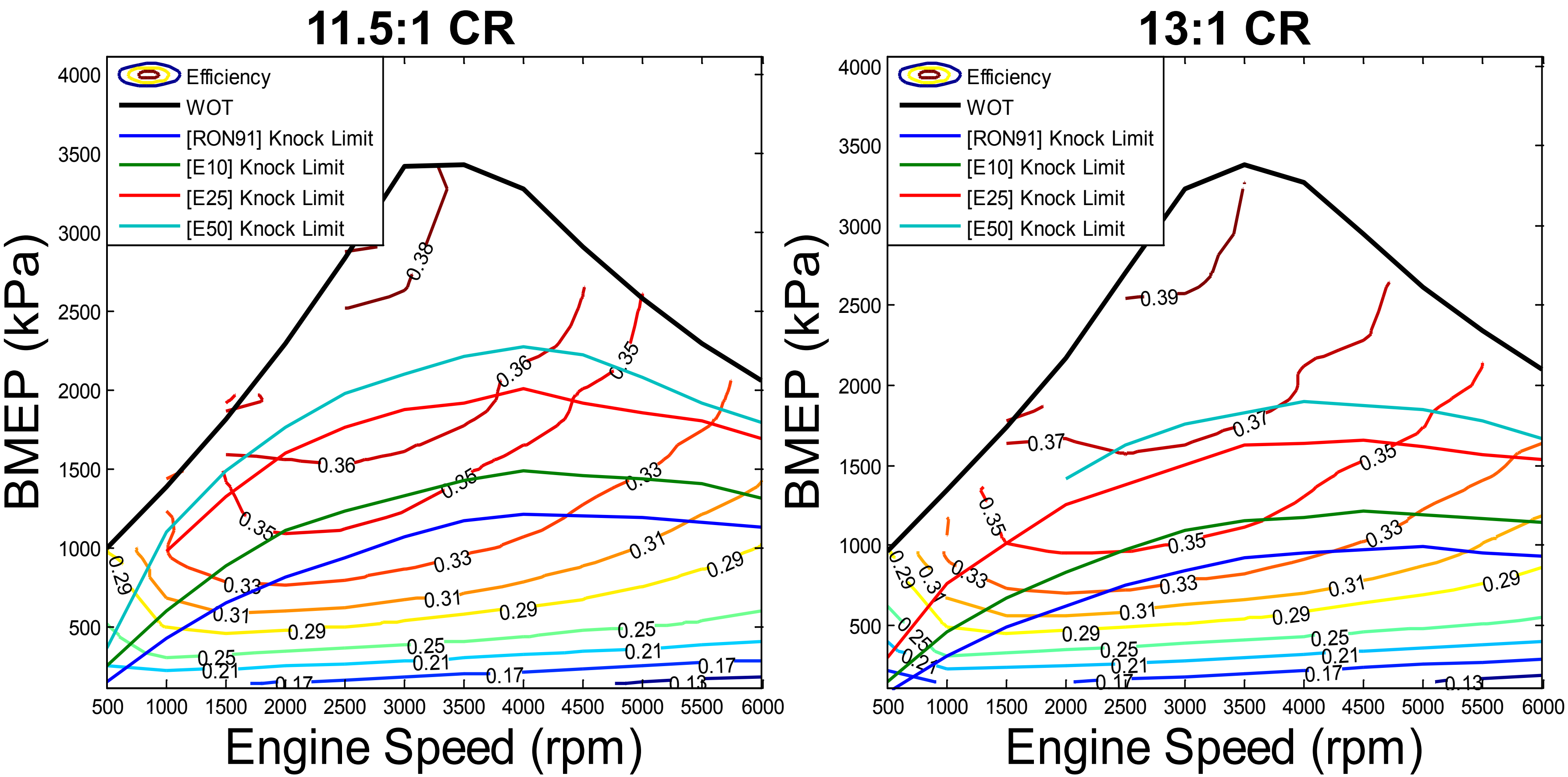
In-Cylinder Peak Pressure Limits

- 100 bar at 1800~1900 kPa BMEP at MBT
- Spark retard necessary above peak pressure limits
- Constraint on boost level and RC

Knock onset limits defined for range of ethanol-gasoline blends, including effects of spark retard on torque, efficiency, and knock threshold

Technical Accomplishments

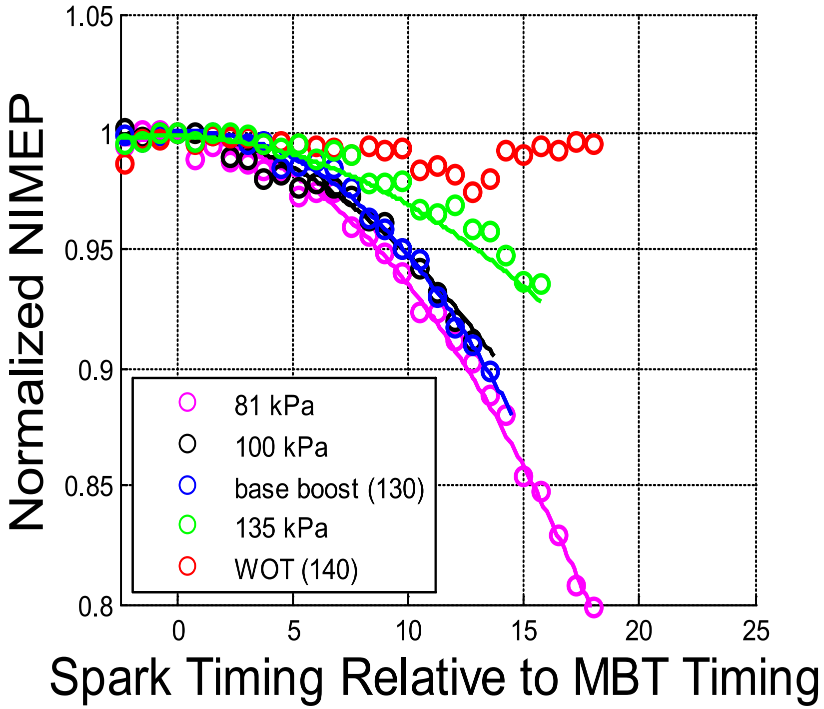
Performance Map at Higher Compression Ratio and Boost

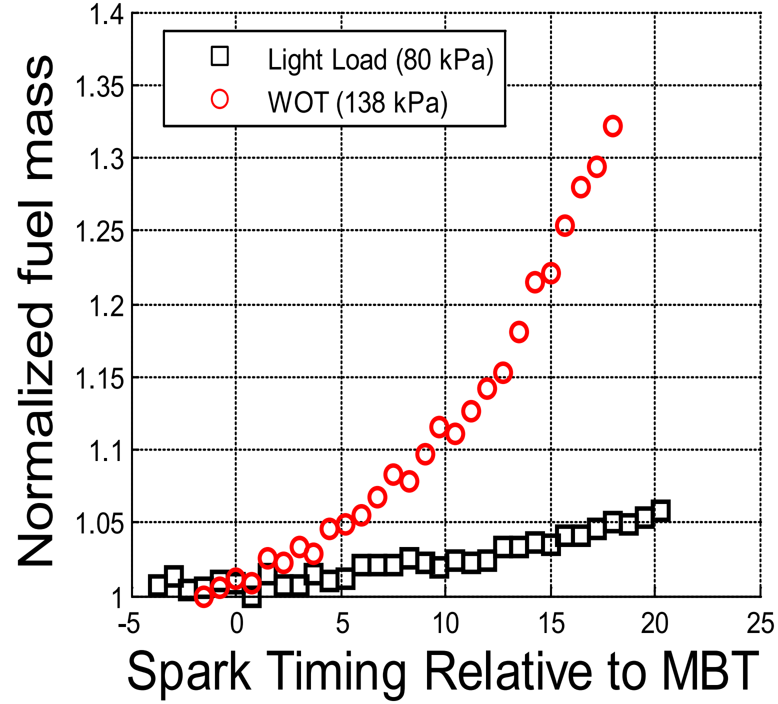


Effects of higher compression ratio and boost on part-load efficiency determined.

Technical Accomplishments

Spark Retard Effect in a TC Engine





- Due to increasing MAP, NIMEP reduction is less at high boost
- Due to increasing MAP, fuel consumption increases with fixed air-to-fuel ratio

Technical Accomplishments

Engine in Vehicle Simulation Approach

Efficiency Map Experiments and simulation at higher CR

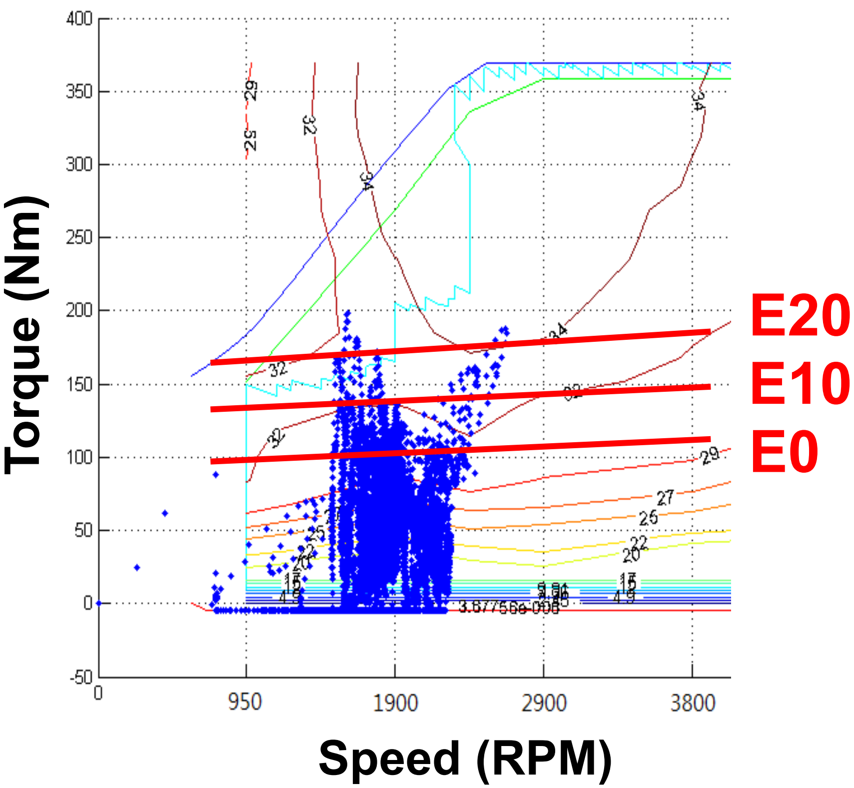
- Fuel Conversion Efficiencies without knock (E85 fuel)
- Knock onset limits for different ethanol blends

Driving Cycle Simulation

- Operation points on the efficiency map determined
- Spark retard incorporated

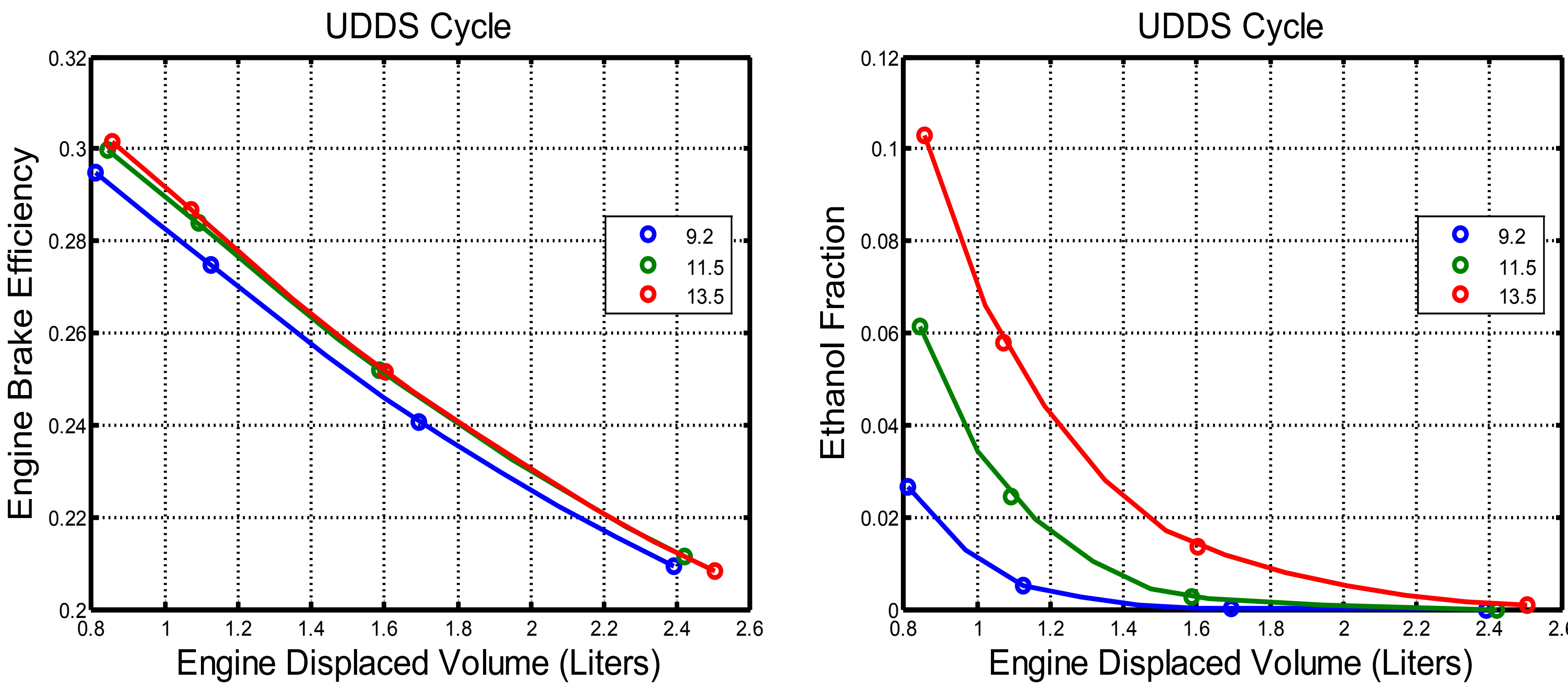
Ethanol consumption

- Ethanol fraction determined at each time step
- Fuel economy determined



Technical Accomplishments

Engine in Vehicle Simulation Results



- Effect of downsizing is large in this this urban driving cycle: improvement in thermal efficiency ~ 40% with downsizing from 2.4 to 1 liter engine
- Impact of increased compression ratio is small
  - little efficiency difference between 11.5 and 13.5

Technical Accomplishments

Illustrative LDV Examples and Results

- 3200 lb. vehicle with 2.5 liter NA engine downsized to 1.25 liter boosted TC engine), CR of 11.5, using up to 10 deg. spark retard when needed:

1. Average engine efficiency and MPG improve 33, 27, and 14% for Urban, Highway, and US06 cycles, respectively, relative to NA engine (average 24%), at constant performance.
2. Ethanol use is 1.5, 0.5, and 8% of gasoline use (on an energy basis): average 3.3%.
3. Use of spark retard important; with MBT spark timing, average efficiency and MPG improves about 4%, but average ethanol use is 15%.
4. Increasing compression ratio from 11.5 to 13.5 has modest effect on efficiency and MPG, but doubles the ethanol consumption.
5. Increasing boost (to 3000 kPa BMEP) and further downsizing to 1 liter engine (at CR of 11.5) increases average efficiency by an additional 15%, but increases average ethanol use to 7.5%.

Collaboration and Coordination with Other Institutions

- MIT leading the effort
  - Experiments with lower pressure capability engine
  - Simulations (chemical/knock, TC engine, vehicle)
  - MIT team: John Heywood, Leslie Bromberg, Daniel Cohn, Young Suk Jo, Raymond Lewis
- Cummins Inc
  - High pressure capability boosted engine tests
  - Providing co-share for the project
  - Leader: Samuel Geckler

Remaining Challenges/Barriers

- Efficiency
  - Met project objective (improvement in efficiency by >25%) in lightly loaded cycles (Urban, Highway), but not US06
  - We have not reached target best thermal efficiency of 45% for LDV
- Ethanol Consumption
  - Relatively high rate-of-consumption of high octane fuel in aggressive cycles
  - Lack of widespread availability of high octane fuel (*i.e.*, E85) could be an issue

Proposed Future Work

- FY14:
  - Evaluation of alcohol enhancement in medium duty vehicles using Autonomie models for multiple drive cycles
  - Evaluation of hydrous ethanol for light duty vehicles
  - Explore engine's octane requirement over full load range
- FY15 (No-cost extension):
  - Determination of cost of implementing technology onboard vehicles
    - Cost of technology
    - Cost of engine and vehicle calibration
    - Cost of ownership

Summary

Project Accomplishments to date

1. Developed broader understanding of turbocharged gasoline engine performance maps, incorporating maximum pressure limits, fuel octane and knock onset constraints, effects of spark retard, higher boost/downsizing trade-off.

2. Demonstrated that ethanol's knock suppressing potential is substantial, and will achieve project's goals: combination of chemical octane and evaporative cooling impact.

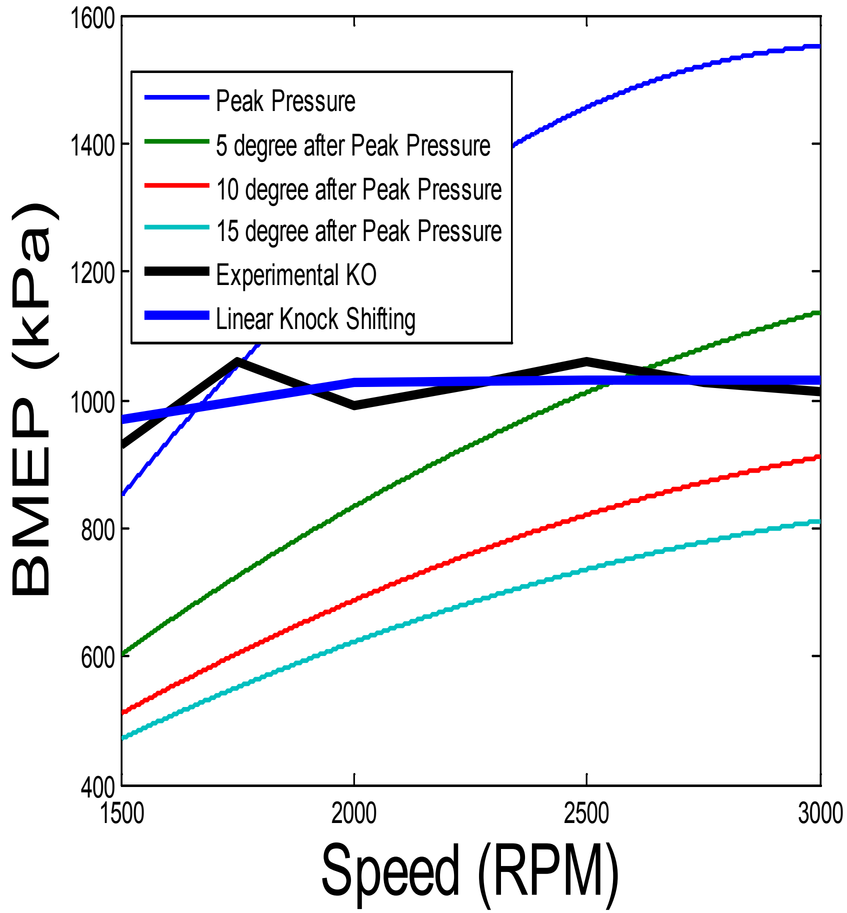
3. Quantified effects of higher compression ratios and higher boost on performance and efficiency of knock-suppressed engine: raising boost with engine downsizing has much larger impact.

4. Engine-in-vehicle simulations, with high compression ratio, high boost, and major engine downsizing indicate up to some 40 percent improved average engine efficiency and miles per gallon (urban driving) at essentially the same vehicle acceleration performance, relative to a naturally-aspirated gasoline engine.

Technical Backup Slides

Technical Accomplishments

Knock Onset and Speed



Knock Limits in Simulation

- Autoignition integral

$$\int_{IVC}^{KO} \frac{dt}{\tau} = 1$$

- KO (Knock Onset) timing changes knock limit in simulation

Knock Limits in Experiments

- Knock onset occurs later after peak pressure as speed increases
- KO insensitive to speed as both KLSA and MBT timing advance

Empirical autoignition knock model has been developed, validated, and used to define knock onset for E0 to E85 on these simulated maps.