Research and
Advanced Engineering

Advanced Gasoline Turbocharged Direct Injection (GTDI) Engine Development

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Ford Research and Advanced Engineering

05/13/2011

Project ID: ACE065

Overview

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- Timeline
  - Project Start 10/01/2010
  - Project End 12/31/2014
  - Completed 10%
- Barriers
  - Gasoline Engine Thermal Efficiency
  - Gasoline Engine Emissions
  - Gasoline Engine Systems Integration
- Total Project Funding
  - DOE Share $15,000,000.
  - Ford Share $15,000,000.
  - Funding in FY2010 $ 3,023,356.
  - Funding in FY2011 $10,365,344.
- Partners
  - Lead Ford Motor Company
  - Support Michigan Technological University (MTU)

Background

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- Ford Motor Company proposed a 4½ year project addressing the solicitation from the Department of Energy Recovery Act – Systems Level Technology Development, Integration, and Demonstration for Efficient Class 8 Trucks (Super Truck) and Advanced Technology Powertrains for Light-Duty Vehicles (ATP-LD) Funding Opportunity Number: DE-FOA-0000079. Ford's proposal was directed toward Area of Interest 2 Advanced Technology Powertrains for Light Duty Vehicles (ATP-LD).

- The project is called "Advanced Gasoline Turbocharged Direct Injection (GTDI) Engine Development". The project is led by Ford Motor Company and supported by MTU. The project director / principal investigator at Ford Motor Company is Corey Weaver. The project director / principal investigator at MTU is Jeffrey Naber.

- The project award number is DE-EE0003332.

Background

- Ford Motor Company has invested significantly in Gasoline Turbocharged Direct Injection (GTDI) engine technology in the near term as a cost effective, high volume, fuel economy solution, marketed globally as EcoBoost technology.

- Ford envisions further fuel economy improvements in the mid & long term by further advancing the EcoBoost technology.
  - Advanced dilute combustion w/ cooled exhaust gas recycling & advanced ignition
  - Advanced lean combustion w/ direct fuel injection & advanced ignition
  - Advanced boosting systems w/ active & compounding components
  - Advanced cooling & aftertreatment systems

Objectives

- Ford Motor Company Objectives:
  - Demonstrate 25% fuel economy improvement in a mid-sized sedan using a downsized, advanced gasoline turbocharged direct injection (GTDI) engine with no or limited degradation in vehicle level metrics.
  - Demonstrate vehicle is capable of meeting Tier 2 Bin 2 emissions on FTP-75 cycle.

- MTU Objectives:
  - Support Ford Motor Company in the research and development of advanced ignition concepts and systems to expand the dilute / lean engine operating limits.

Approach

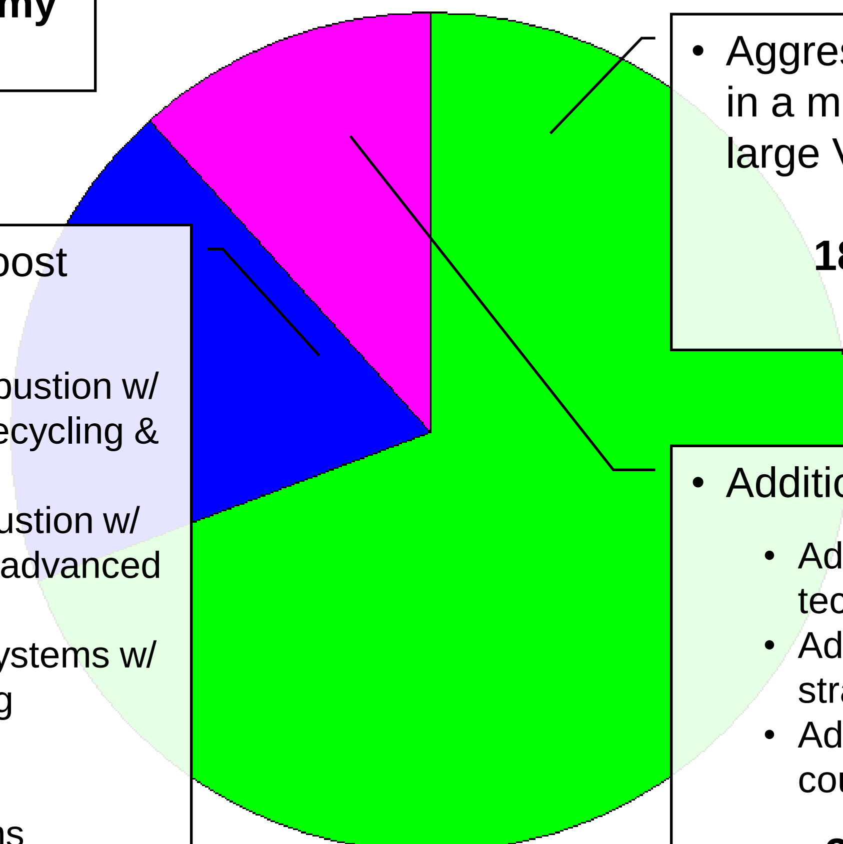
- Engineer a comprehensive suite of gasoline engine systems technologies to achieve the project objectives, including:
  - Aggressive engine downsizing in a mid-sized sedan from a large V6 to a small I4
  - Mid & long term EcoBoost technologies
    - Advanced dilute combustion w/ cooled exhaust gas recycling & advanced ignition
    - Advanced lean combustion w/ direct fuel injection & advanced ignition
    - Advanced boosting systems w/ active & compounding components
    - Advanced cooling & aftertreatment systems
  - Additional technologies
    - Advanced friction reduction technologies
    - Advanced engine control strategies
    - Advanced NVH countermeasures
- Progressively demonstrate the project objectives via concept analysis / modeling, single-cylinder engine, multi-cylinder engine, and vehicle-level demonstration on chassis rolls.

Approach

Research and Advanced Engineering

- Engineer a comprehensive suite of gasoline engine systems technologies to achieve the project objectives, including:

25% Total Fuel Economy Improvement



- Aggressive engine downsizing in a mid-sized sedan from a large V6 to a small I4

18% Fuel Economy Improvement

- Mid & long term EcoBoost technologies
  - Advanced dilute combustion w/ cooled exhaust gas recycling & advanced ignition
  - Advanced lean combustion w/ direct fuel injection & advanced ignition
  - Advanced boosting systems w/ active & compounding components
  - Advanced cooling & aftertreatment systems

5% Fuel Economy Improvement

- Additional technologies
  - Advanced friction reduction technologies
  - Advanced engine control strategies
  - Advanced NVH countermeasures

3% Fuel Economy Improvement

Milestone Timing

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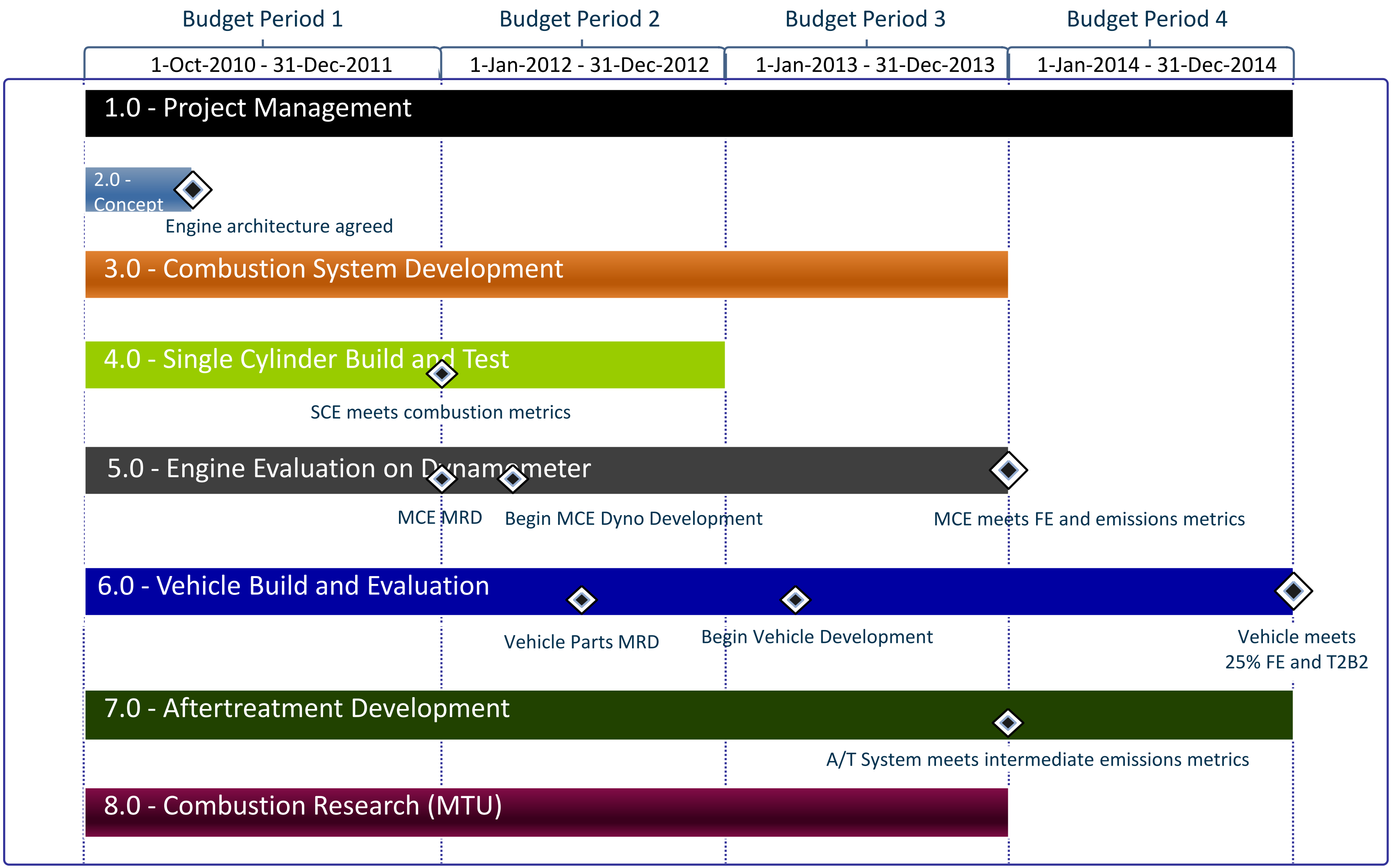

Milestone Deliverables

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Budget Period	Timing	Deliverables
BP1 – Concept Analysis and Design	1-Oct-2010 – 31-Dec-2011	• Engine architecture agreed • Analytical results support ability to meet fuel economy • Multi-cylinder development engines designed and parts purchased • Single-cylinder development shows capability to meet intermediate combustion metrics supporting fuel economy and emissions objectives
BP2 – Engine Development	1-Jan-2012 – 31-Dec-2012	• Multi-cylinder development engines completed and dynamometer development started • Demonstration vehicle and components available to start build and instrument
BP3 – Engine and Vehicle Development	1-Jan-2013 – 31-Dec-2013	• Dynamometer engine development indicates capability to meet intermediate metrics supporting vehicle fuel economy and emissions objectives • Vehicle built, instrumented, and development work started • Aftertreatment system development indicates capability to meet intermediate metrics supporting emissions objectives
BP4 – Vehicle Development	1-Jan-2014 – 31-Dec-2014	• Vehicle demonstrates greater than 25% weighted city/highway fuel economy improvement and T2B2 emissions on FTP-75 test cycle

Accomplishments

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- Task 1.0 – Project Management
  - Completed Ford / DOE Kick-Off Meeting – Ford Advanced GTDI Engine Development – 11/30/2010
  - Submitted Petition for Advance Patent Waiver Rights and Updated Program Management Plan – 11/30/2010

- Task 2.0 – Concept Evaluation
  - Top level engine attribute assumptions, architecture assumptions, and systems assumptions developed to support program targets.
  - Detailed fuel economy, emissions, performance, and NVH targets developed to support top-level assumptions.
  - Individual component assumptions developed to support detailed targets, as well as to guide combustion system, single-cylinder engine, and multi-cylinder engine design & development.
  - Initiated detailed, cycle-based CAE analysis of fuel economy contribution of critical technologies to ensure vehicle demonstrates greater than 25% weighted city / highway fuel economy improvement.

Accomplishments

- Task 3.0 – Combustion System Development
  - Completed detailed MESIM (Multi-dimensional Engine SIMulation) analyses to design & develop an advanced combustion system, inclusive of intake & exhaust ports, combustion chamber, piston top surface, and injector specifications.
  - Incorporated surrogate single-cylinder engine data to design & develop the advanced lean combustion capability, with primary emphasis on maximizing fuel economy while minimizing NOx & PM emissions.
- Task 4.0 – Single Cylinder Build & Test
  - Generated surrogate single-cylinder engine data to design & develop the advanced lean combustion capability, with primary emphasis on maximizing fuel economy while minimizing NOx & PM emissions. Testing included air-fuel ratio sweeps, multiple injection split and timing sweeps, cooled EGR sweeps, and cam timing sweeps.
  - Utilizing accomplishments from Task 3.0, completed design of new single-cylinder engine and ordered components to support single-cylinder build & test.

Advanced Lean Combustion

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- Various lean combustion concepts have been investigated, each with material fuel economy increases, but each with unique challenges
- Advanced lean combustion appears promising, approaching ideal function with further development

Ideal Lean

- ✓ Good Fuel Economy
- ✓ Low NOx Emissions
- ✓ Low PM Emissions
- ✓ Practicable Controls
- ✓ Acceptable NVH

Homogeneous Lean

- ✓ Good Fuel Economy
- ☹ Low NOx Emissions
- ✓ Low PM Emissions
- ✓ Practicable Controls
- ✓ Acceptable NVH

Stratified Lean

- ✓ Good Fuel Economy
- ☹ Low NOx Emissions
- ☹ Low PM Emissions
- ✓ Practicable Controls
- ✓ Acceptable NVH

Advanced Lean

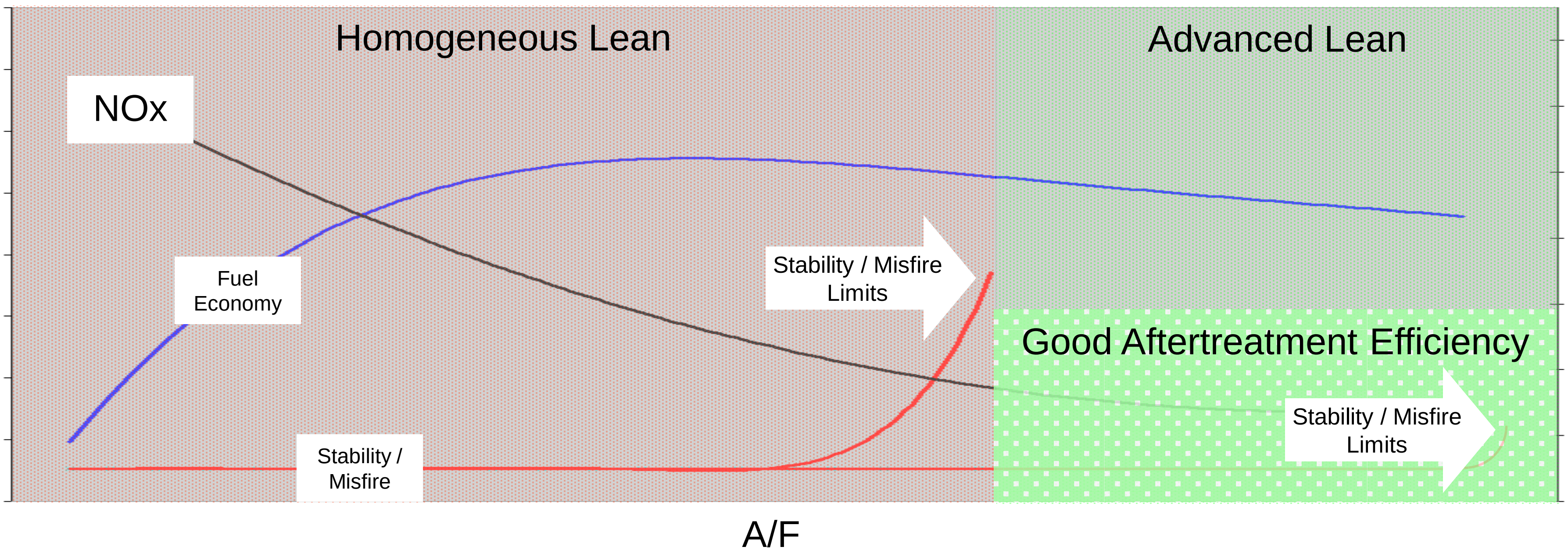
- ✓ Good Fuel Economy
- ✓ Low NOx Emissions
- ✓ Low PM Emissions
- ✓ Practicable Controls
- ✓ Acceptable NVH

Advanced Lean Combustion

- NOx decreases as A/F ratio increases, favoring NOx aftertreatment efficiency
- Fuel economy increases as air / fuel ratio increases

☹ Homogeneous lean combustion constrained by stability / misfire limits

☺ Advanced lean combustion extends combustion stability / misfire limits



Accomplishments

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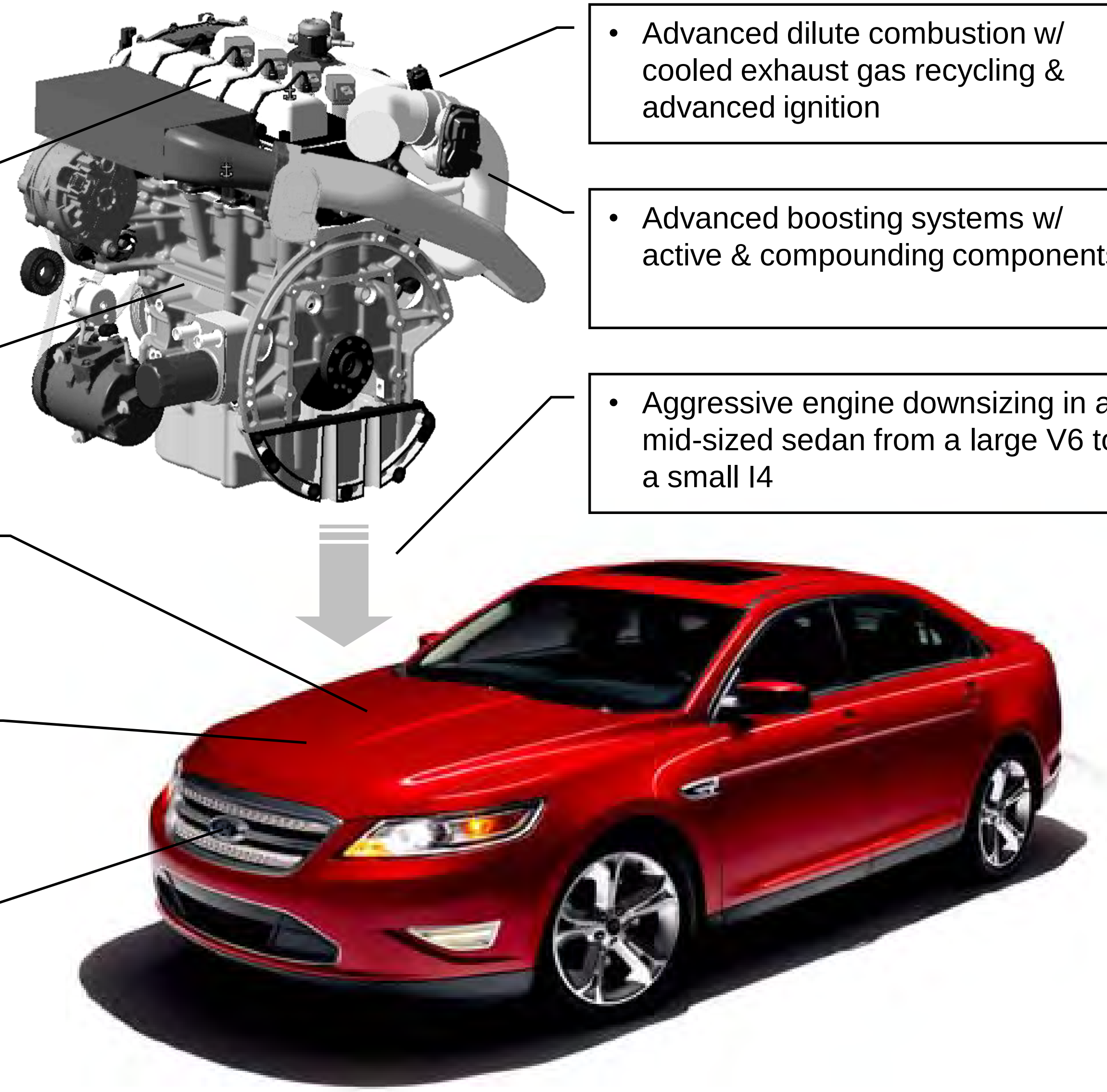
- Task 5.0 – Engine Evaluation on Dynamometer
  - Utilizing accomplishments from Tasks 2.0 & 3.0, initiated CAD design of new multi-cylinder engine, inclusive of all base engine components, advanced engine systems, and advanced integrated powertrain systems.
  - Initiated required CAE analyses (acoustic, structural, thermal-mechanical, etc.), in support of CAD design of critical components and systems.
  - Completed first-pass design of base engine components and generated SLA models for component and manufacturing engineering review.

- Task 6.0 – Vehicle Build and Evaluation
  - Completed first-pass CAE analysis of total engine & vehicle cooling system, with primary emphasis on internal engine cooling flow to optimize the split, reverse, cross-flow cooling configuration.

Concept Analysis and Design

- A comprehensive suite of gasoline engine systems



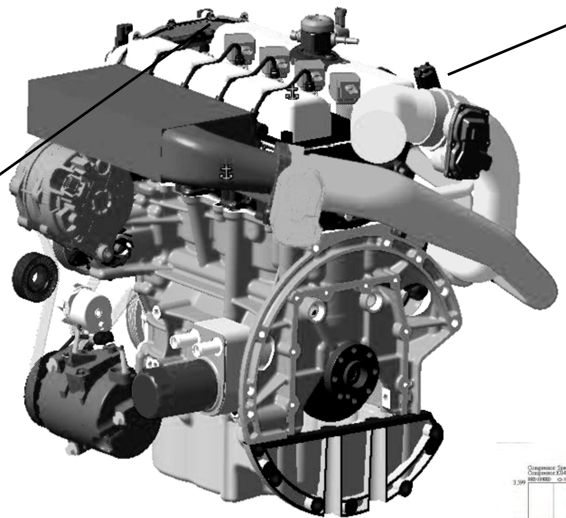
- Advanced lean combustion w/ direct fuel injection & advanced ignition
- Advanced friction reduction technologies
- Advanced engine control strategies
- Advanced NVH countermeasures
- Advanced cooling & aftertreatment systems
- Advanced dilute combustion w/ cooled exhaust gas recycling & advanced ignition
- Advanced boosting systems w/ active & compounding components
- Aggressive engine downsizing in a mid-sized sedan from a large V6 to a small I4

Concept Analysis and Design

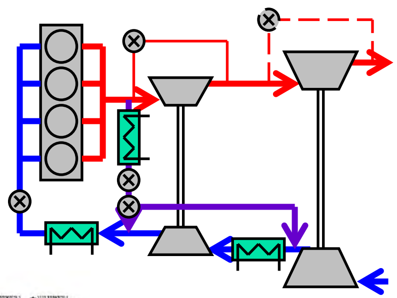
Research and Advanced Engineering

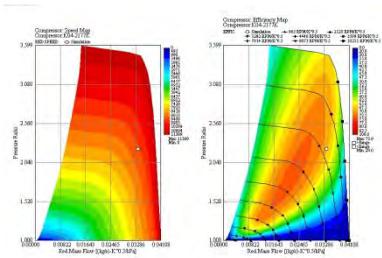
- A comprehensive suite of CAE analyses

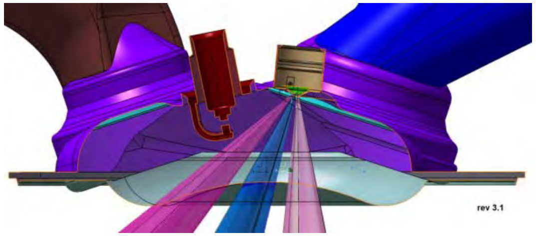
- Three Dimensional Engine Simulation
  - Intake & exhaust ports
  - Combustion chamber
  - Piston top surface
  - Injector specifications

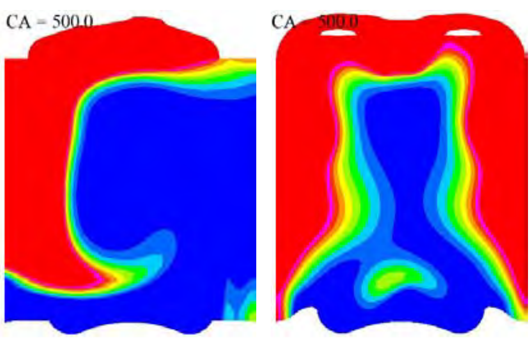


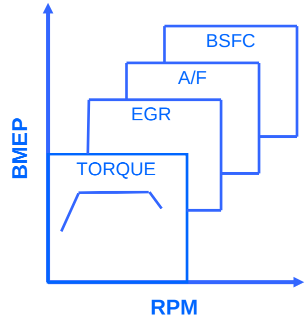
- Quasi / One Dimensional Engine Simulation
  - Boost system matching











- Cycle-based CAE analysis of fuel economy contribution of critical technologies
- High confidence multi-cylinder engine design to achieve the project objectives
- Controls & calibration challenges identified and respective workplans developed

Accomplishments

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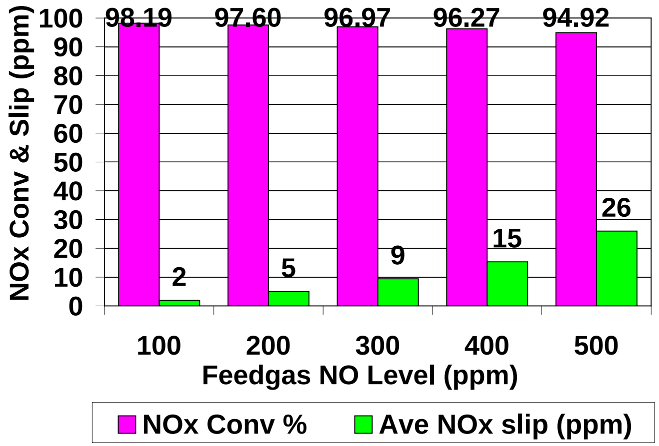
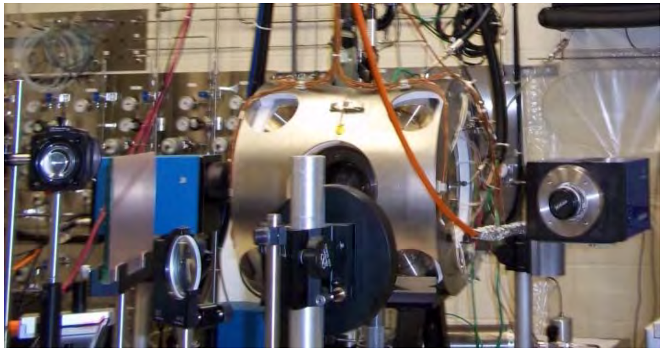
- Task 7.0 – Aftertreatment Development
  - NOx conversion data collected on laboratory flow reactor with TWC + Advanced LNT catalyst system during lean / rich cycling.
    - Tests performed with different feedgas NO levels demonstrate lower feedgas NO levels significantly decrease NOx slip, thereby improving potential to achieve Tier 2 Bin 2 NOx emissions.
    - Target range of feedgas NOx levels specified; combustion team working to achieve these engine-out NOx emission levels.

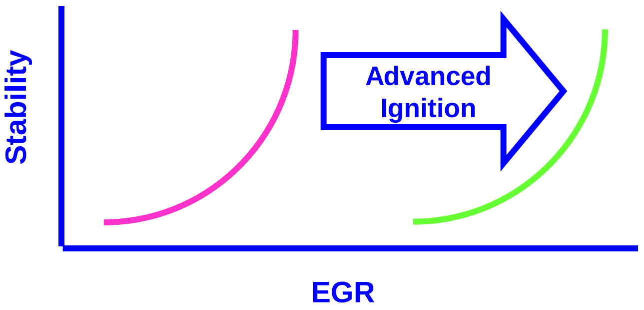


  - Laboratory flow reactor work directed toward optimizing exhaust conditions in order to achieve high conversions of HC and NOx simultaneously.
    - TWC catalyst and Advanced LNT catalyst system placed in different ovens to allow different temperatures for catalysts.
    - Using target feedgas NOx levels, demonstrated very high HC and NOx conversions with aged catalyst samples by optimizing lean / rich cycle times and individual temperatures and volumes of TWC catalyst and Advanced LNT catalyst system.

Collaboration

- Task 8.0 – Combustion Research (MTU)
  - Advanced Ignition & Flame Kernel Development
    - Custom ignition hardware & software shipped & installed on combustion vessel at MTU.
    - Graduate students trained in operation of ignition hardware & software.
    - Gaseous fuel mixture selected as surrogate for gasoline fuel.
  - GDI Air / Fuel Mixing via PLIF for Fuel Injection Optimization
    - Characterization of combustion vessel flowfield initiated for subsequent air / fuel mixing studies.
  - Advanced Ignition - Impact on Combustion
    - V6 EcoBoost engine installed and running break-in on dynamometer at MTU; cooled EGR hardware shipped to MTU for installation on engine.
    - Graduate students trained in operation of engine control module calibration parameters.





Future Work

- Budget Period 1 – Concept Analysis and Design 10/01/2010 – 12/31/2011
  - Engine architecture agreed
  - Analytical results support ability to meet fuel economy
  - Multi-cylinder development engines designed and parts ordered
  - Single-cylinder development shows capability to meet intermediate combustion metrics supporting fuel economy and emissions objectives

- Budget Period 2 – Engine Development 01/01/2012 – 12/31/2012
  - Multi-cylinder development engines completed and dynamometer development started
  - Demonstration vehicle and components available to start build and instrument

Summary

Research and Advanced Engineering

- The project will demonstrate a 25% fuel economy improvement in a mid-sized sedan using a downsized, advanced gasoline turbocharged direct injection (GTDI) engine with no or limited degradation in vehicle level metrics, while meeting Tier 2 Bin 2 emissions on FTP-75 cycle.

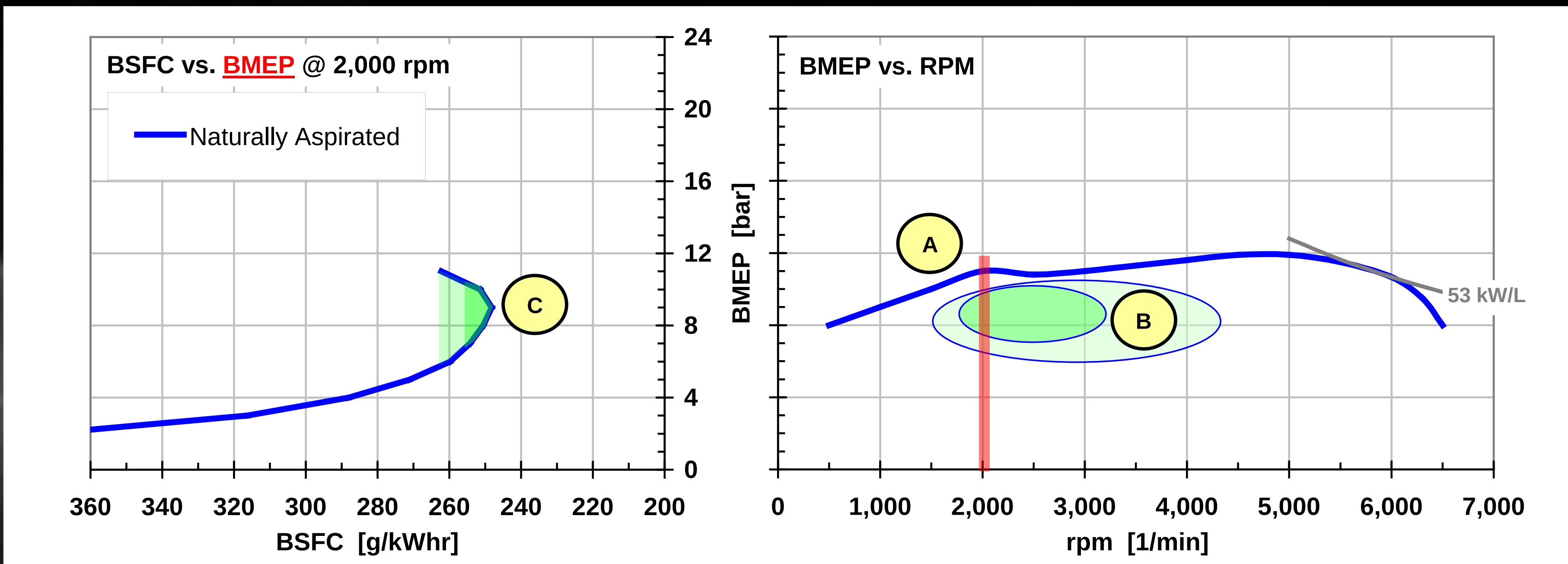
- Ford Motor Company has engineered a comprehensive suite of gasoline engine systems technologies to achieve the project objectives, assembled a cross-functional team of subject matter experts, and progressed the project through the concept analysis and design tasks with material accomplishments to date.

- Ford Motor Company is in collaboration with Michigan Technological University on a critical facet of the project, specifically advanced ignition concepts.

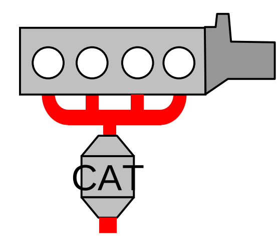
- With the project recently initiated on 10/01/2010, there are no key issues beyond the original scope of work. The outlook for 2011 is stable, with accomplishments anticipated to track the original scope of work and planned tasks.

Technical Back-Up

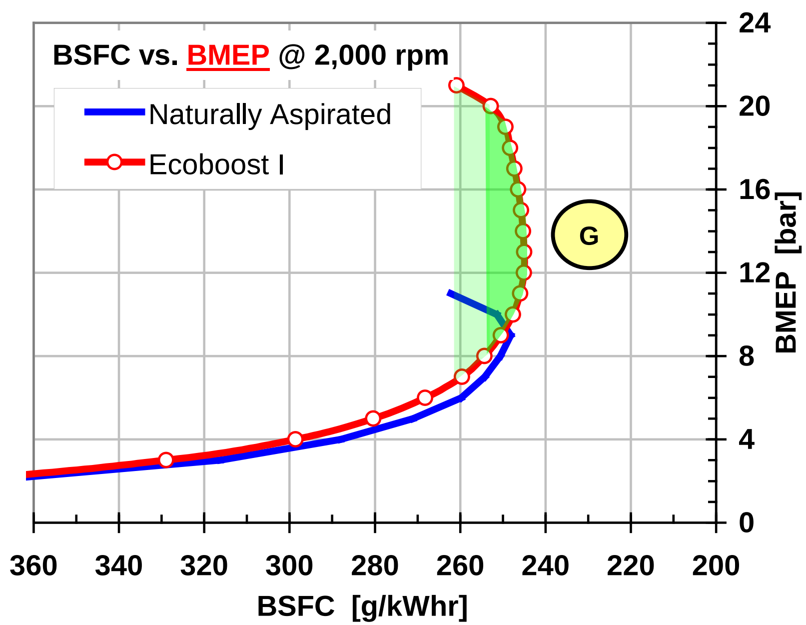
EcoBoost Physics – Baseline

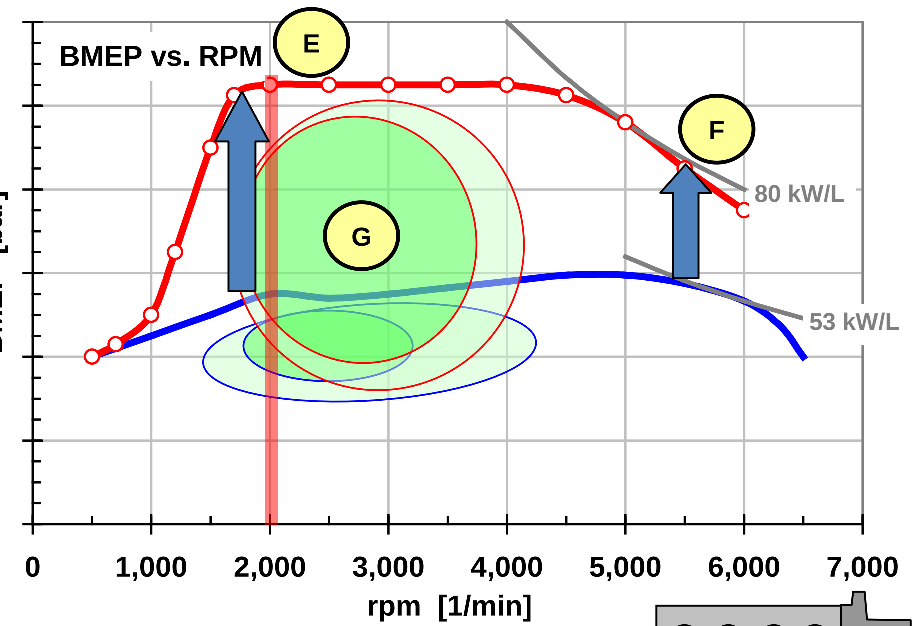


- Baseline: Naturally-aspirated, port fuel injected engine
  - Torque / liter modest (A)
  - Good BSFC over small region of map (B)
  - Fuel consumption favorable only at high load (C)

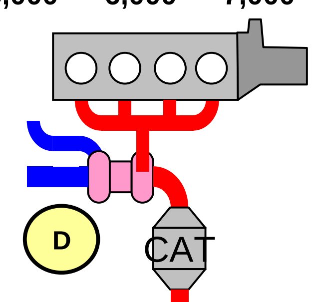


EcoBoost Physics – 1 / 3 – Boost & Direct Inject

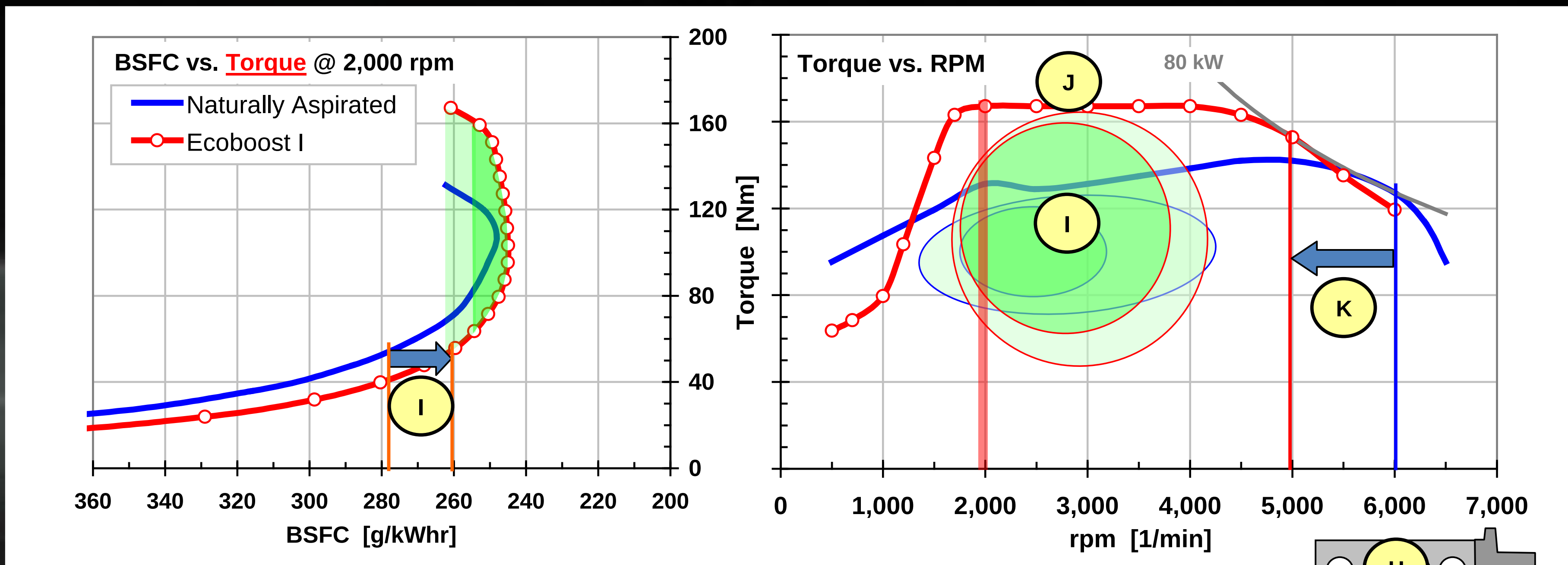


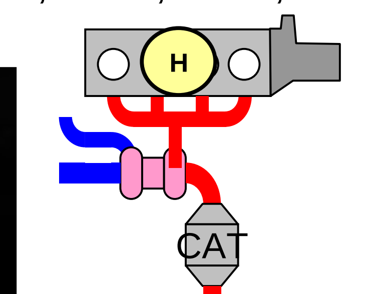


- Step 1: Boosted, direct fuel injected engine (D)
  - Torque / liter nearly 2X (E) Power / liter nearly 1.3 – 1.5X (F)
  - Good BSFC over larger region of engine map (G)
  - Direct fuel injection needed to minimize compression ratio loss (i.e. charge cooling)



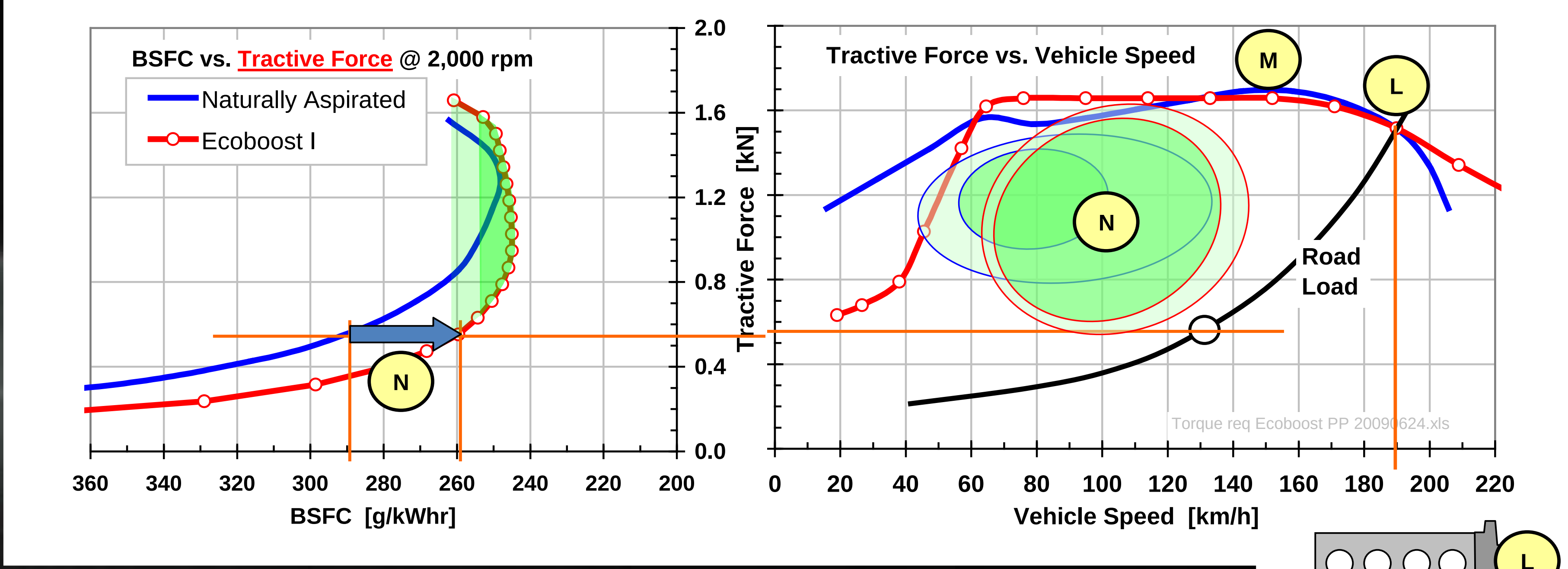
EcoBoost Physics – 2 / 3 – Downsize





- Step 2: Downsize engine to equal power (H)
  - Nearly 1/3 lower displacement (i.e. V8 ⇨ V6, V6 ⇨ I4, I4 ⇨ I3)
  - Good BSFC region of engine map shifted to area of higher utilization (I)
  - Excess torque ☺ (J) Potential to downspeed engine (K)

EcoBoost Physics – 3 / 3 – Downspeed



- Step 3: Downspeed engine to equal vehicle top speed **L**
  - Tractive force equals naturally aspirated baseline **M**
  - Application considerations needed (e.g. gradability, towing)
  - Good BSFC region of engine map shifted to area of higher utilization **N**