Recent Engine Combustion Activities at the ERC and in the US

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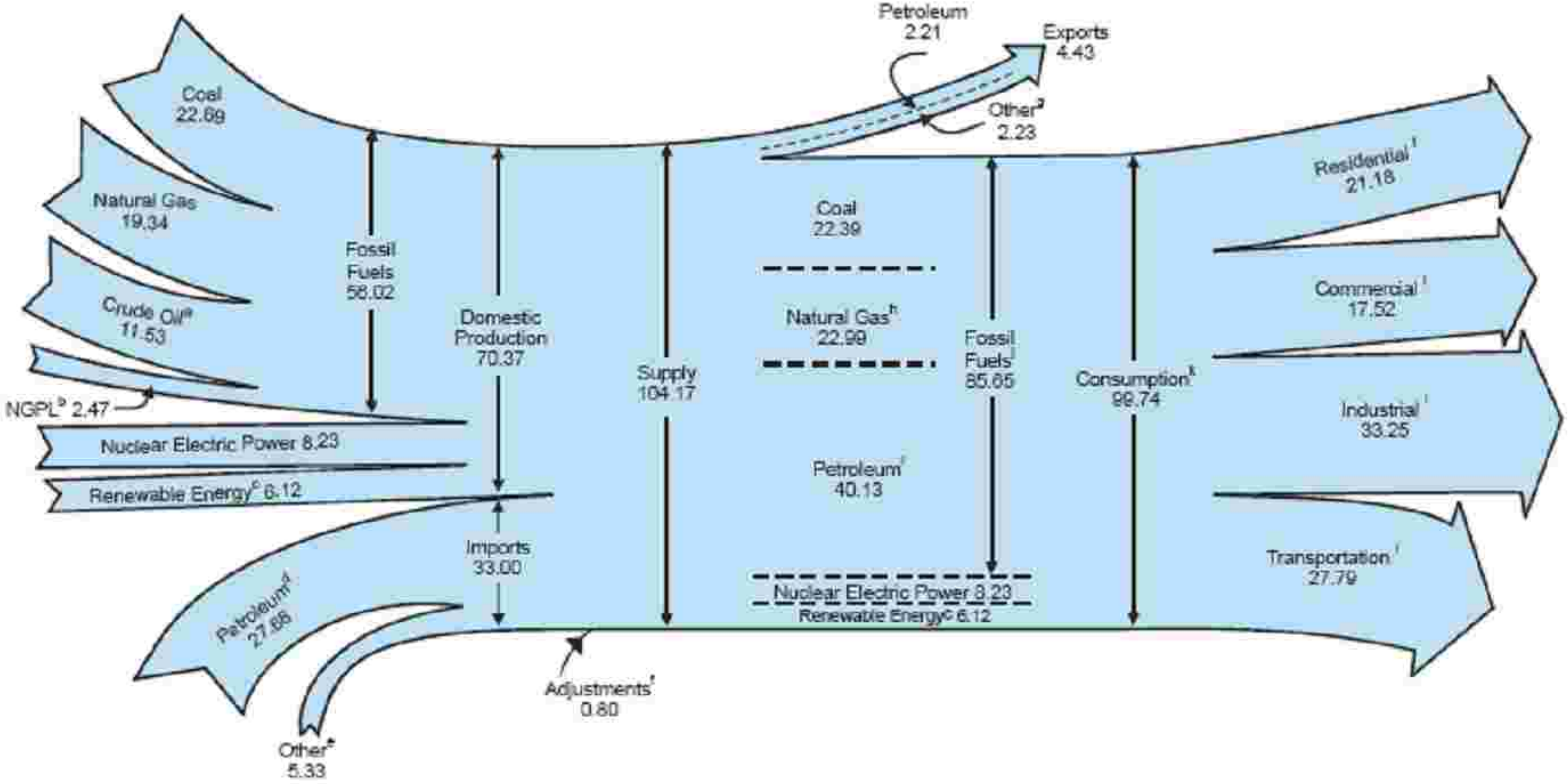
Outline

- Very general comments about US Fuel Situation:
  - Energy Situation
  - Fuel Supply
    - My opinion of what are the drivers for change in the US
    - How bio-fuel fits in to this picture
- Research Trends in the US
- Selected overview of research at the ERC
  - Typical of US in general
  - Comments as to the relevance to bio-fuels
- Summary comments

US Energy Flow (Quadrillion BTU's)



[a] Includes lease condensate.
[b] Natural gas plant liquids.
[c] Conventional hydroelectric power, wood, waste, ethanol blended into motor gasoline, geothermal, solar, and wind.
[d] Crude oil and petroleum products. Includes imports into the Strategic Petroleum Reserve.
[e] Natural gas, coal, coal coke, and electricity.
[f] Stock changes, losses, gains, miscellaneous blending components, and unaccounted-for supply.
[g] Coal, natural gas, coal coke, and electricity.
[h] Includes supplemental gaseous fuels.
[i] Petroleum products, including natural gas plant liquids.
[j] Includes 0.14 quadrillion Btu of coal coke net imports.
[k] Includes, in quadrillion Btu, 0.30 ethanol blended into motor gasoline, which is accounted for in both fossil fuels and renewable energy but counted only once in total consumption; and 0.04 electricity net imports.
[l] Primary consumption, electricity retail sales, and electrical system energy losses, which are allocated to the end-use sectors in proportion to each sector's share of total electricity retail sales. See Note, "Electrical Systems Energy Losses," at end of Section 2.

Notes: • Data are preliminary. • Totals may not equal sum of components due to independent rounding.

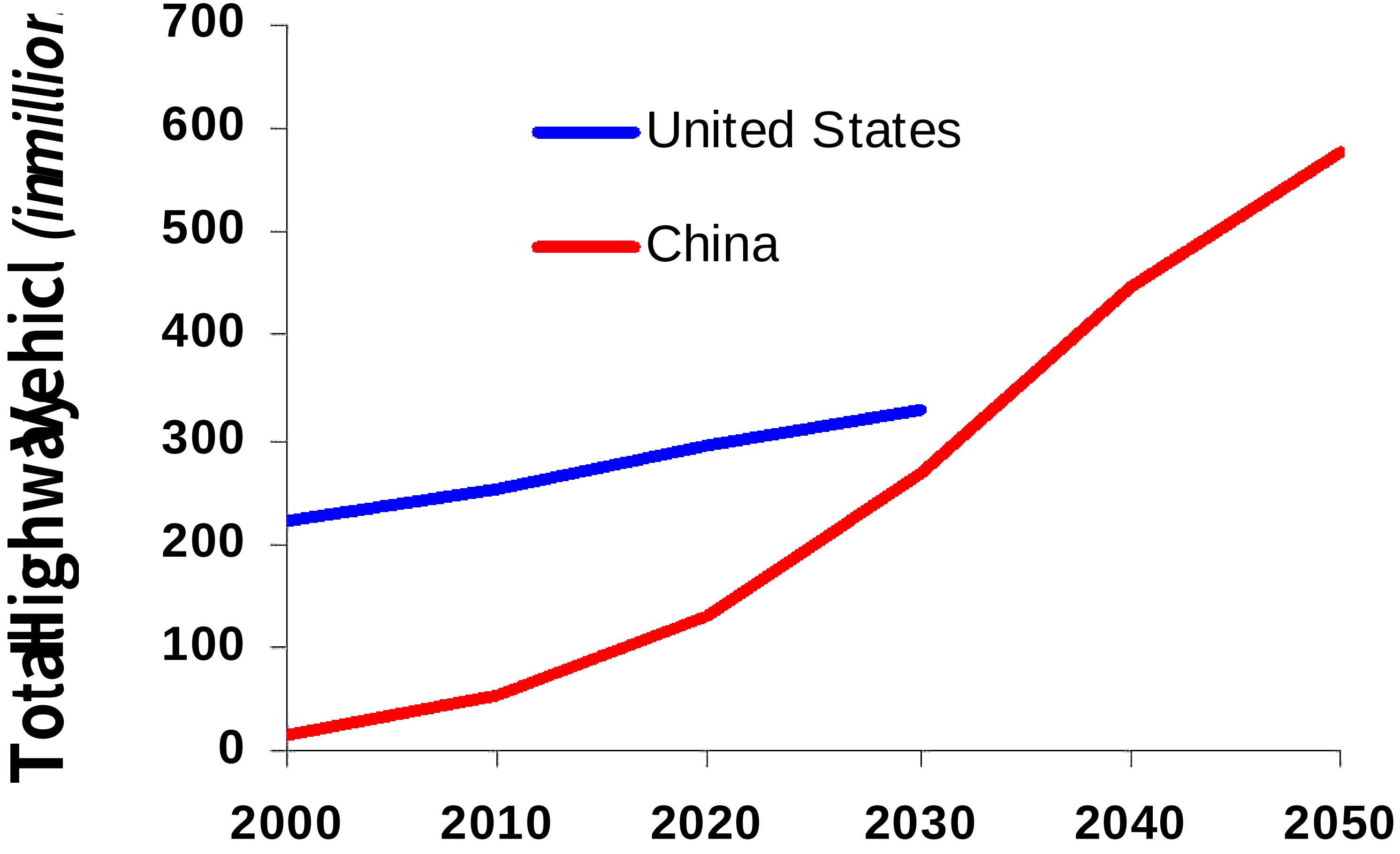
Sources: Tables 1.1, 1.2, 1.3, 1.4, 2.1a, and 10.1.

Energy Information Administration / Annual Energy Review 2004

Fuel Consumption Has Become a Politically Important Issue in the US

- **CO2 Emission has become a public issue in the US**
  - **Working its way up into the political arena**
- **Concern for dependence on "non-domestic" petroleum is leading to increased emphasis on:**
  - **Higher efficiency mobility systems**
    - **Hybrids, PHEV, Fuel cells**
    - **Alternative fuels**
      - **Gas to liquid, Coal liquification, bio-fuels**
      - **Diversification of energy sources**
        - » **H2 as an energy carrier (unclear whether bio-fuels will be a source of hydrogen)**

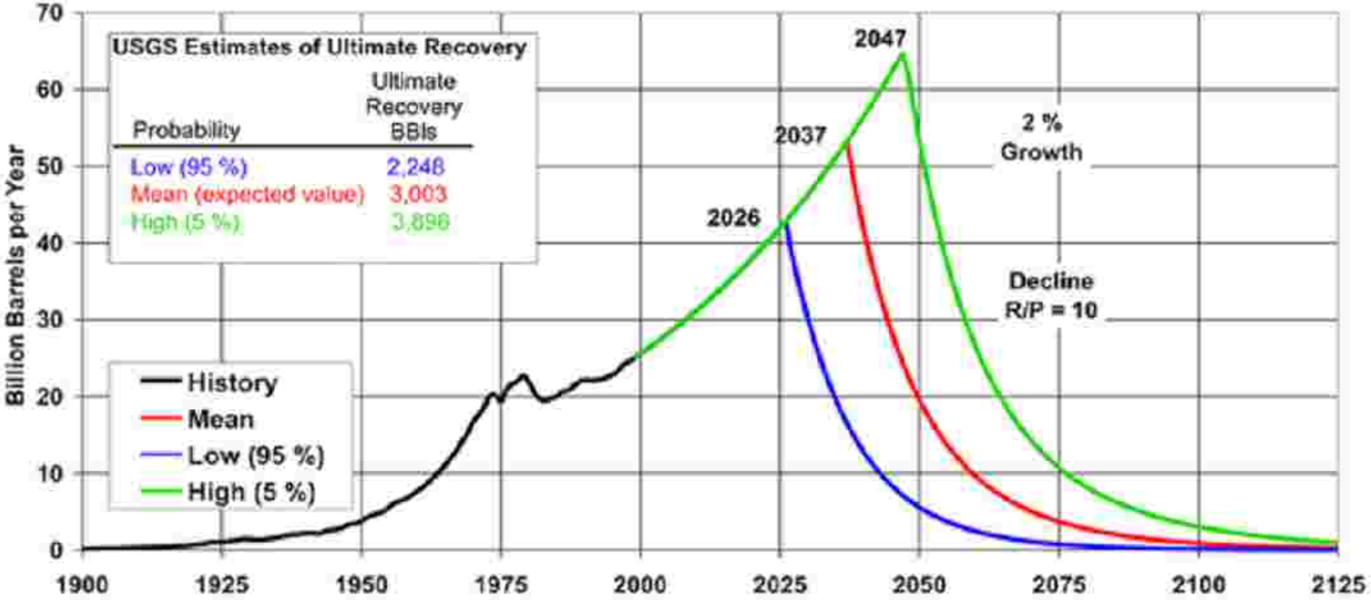
China: Growth in Number of Vehicles in Use



Source: USA Data: EIA, *Annual Energy Outlook 2007*. China Data: Argonne National Laboratory, *"Projection of Chinese Motor Vehicle Growth,"* 2006.

What About Supply? (Hubbert?)

Figure 2. Annual Production Scenarios with 2 Percent Growth Rates and Different Resource Levels (Decline R/P=10)

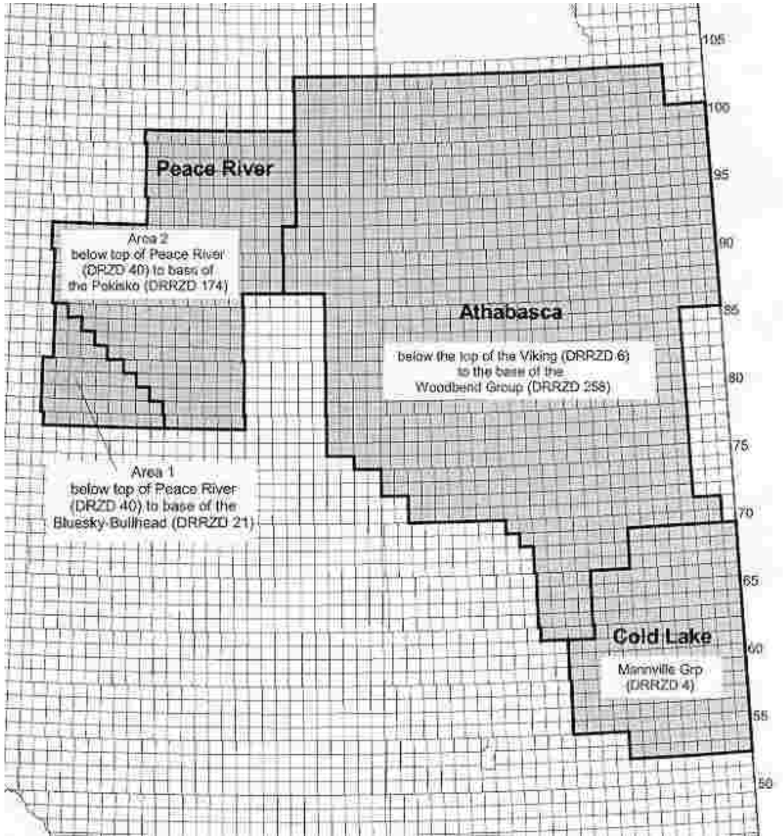


Source: Energy Information Administration
Note: U.S. volumes were added to the USGS foreign volumes to obtain world totals.

http://www.hubbertpeak.com/us/eia/oilsupply2004.htm

Counting Tar Sands

Alberta Canada



- **Alberta Canada**
  - **The total reserves for Alberta, including oil not recoverable using current technology, are estimated at 1,700- 2,500 Gb (billion barrels)***
  - **Saudia Arabia's estimated reserves ~ 240 Gb**
- **Venezuela**
  - **Including tar sands as reserves makes Venezuela, and Canada, dwarf Saudia Arabia as a source of HC fuels.**

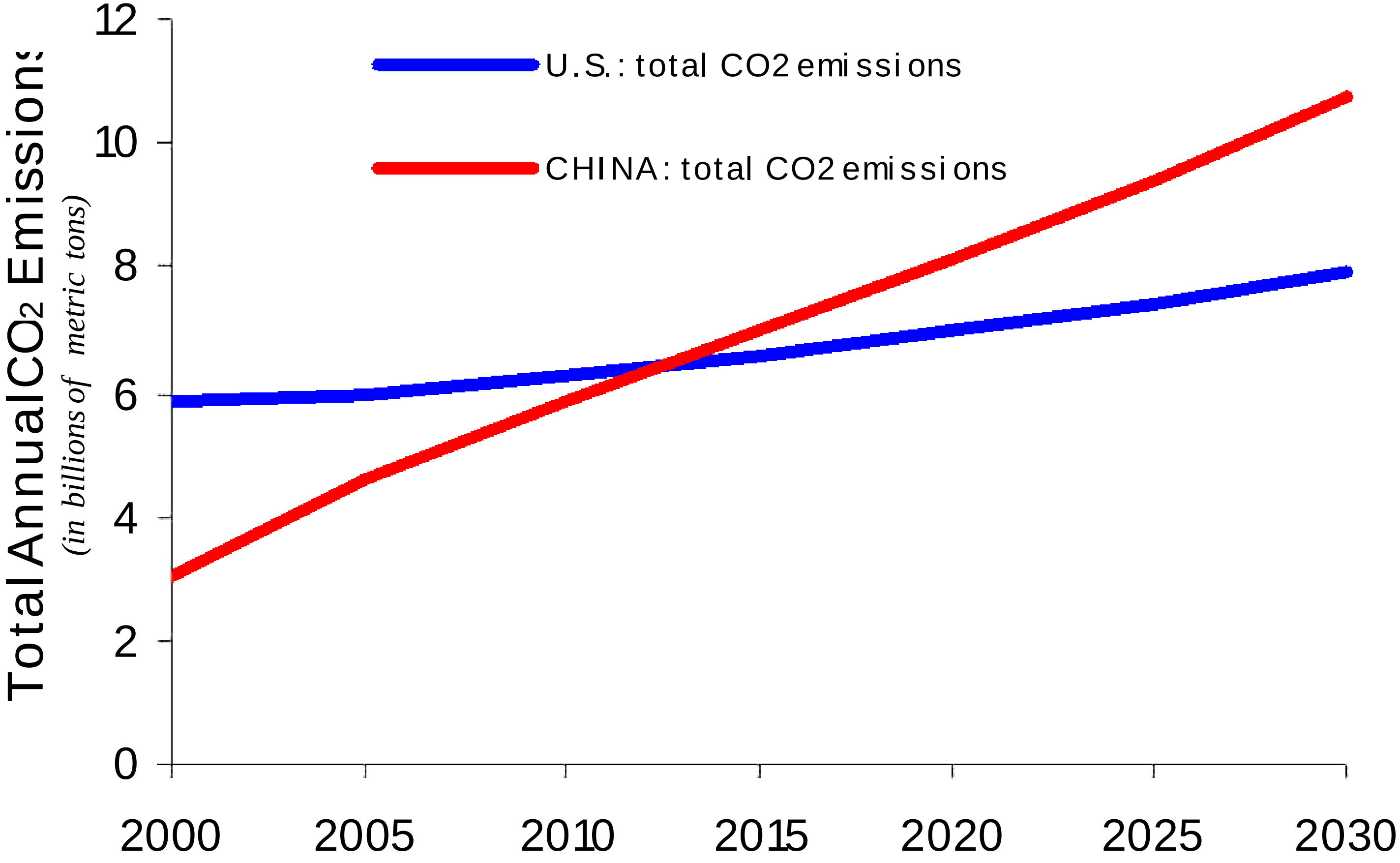
***Readily recoverable reserves ~ 60-70 billion barrels**

http://ffden-2.phys.uaf.edu/102spring2002_Web_projects/M.Sexton/

Is Supply Really an Issue?

- As demand for oil increases, its price will increase
  - More challenging reserves become economically viable – ex. Gulf of Mexico
- Alternatives, like tar sands become viable
  - Canada is currently the largest foreign importer of HC fuels to the US.
- In my opinion supply is not an issue, the real issue is carbon emission
- Processing tar sands, shale oil, coal liquefaction etc., is very carbon emission intensive
  - In this context bio-fuels are very attractive

US & China CO_2 Emissions



Source: Energy Information Administration: *Annual Energy Review 2005, International Energy Annual 2004, Annual Energy Outlook 2007,* & *International Energy Outlook 2006*.

Practical Aspects of Transitioning New Technologies into the Market

- Take the US market as an example:
  - 230 million registered vehicles*
  - Annual sales, approximately 17 million
    - Approximately 14 years to turn the entire fleet over
  - Last year's sales of hybrids, ~ 200,000 (1.18%)
    - Even unimaginably aggressive infusion of hybrids into the market would result in approximately 5% of the market in 14 years
- Consider the most optimistic scenario imaginable:
  - Development of commercially viable Fuel Cell vehicle by 2010
    - Need to implement a new fuel infrastructure (decades?)
    - Implement production capabilities to enable significant fraction of vehicle offerings to be fuel cell vehicles
    - Allowing for fleet turn over – market penetration
    - Time to market penetration of 10 – 15 %, 30 - 50 years??
- Several decades to bring about a perceptible change vehicle fleet

* US News and World Report, February 13, 2006

Quick Assessment

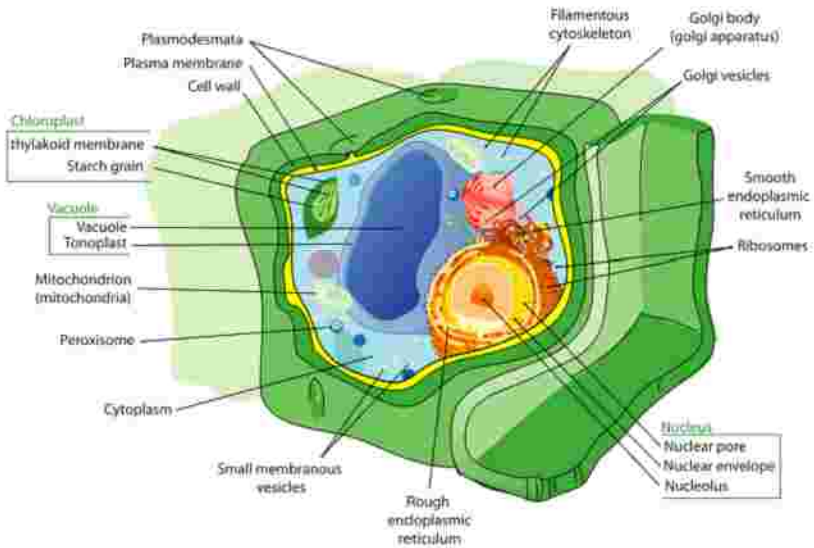
- **Even with very successful development of different powerplants (electric, fuel cell, compressed air) the IC Engine will continue to be the dominant powerplant for mobility systems for many decades to come.**
  - **Total life cycle analysis of energy "use" and CO2 emissions indicate advanced hybrid vehicles will be competitive to proposed alternative powerplants: bio-fuels further reduce the life cycle CO2 of IC Engines**
- **Improvements made to IC engines today will yield an integrated, cummulative, benefit while (if) new technologies do make it to market**

Bio-fuels?

- There is a huge effort to promote the development of bi-fuels within the US
  - US program 20 in 10 (Achieving twenty percent displace ent of petroleum with bio-fuels in 10 years (2017)
  - Major effort to coordinate all the branches within the US government with activities related to bio-fuels
- Many people believe that ethanol from corn will be a minor contributor, at best, to this goal
  - Cellulosic bio-fuels need to be developed
  - Large increases in government funding are being proposed
- Bio fuels are a complicated topic
  - Need to do accurate accounting of all growing, harvest g and processing energy and emissions
  - It appears that Bio fuels can be a contributor to the l pool, but are not THE solution
  - Ethanol from corn ~ a few percent displacement
  - Successful cellulosic bio-fuels program ~ 35% displacement

Cellulosic Technology

1. **Cell walls contain lignin and cellulose***
2. **Use enzymes to break cellulose into sugars**
3. **Ferment sugars into ethanol**
4. **Use lignin as power source**



* www.harvestcleanenergy.org claims roughly 2/3 biomass is cellulose and hemicellulose; rest is mostly lignin

Matt Bowen, National Academies Staff Talk, November 14th, 2006

Cellulosic Ethanol from Switchgrass

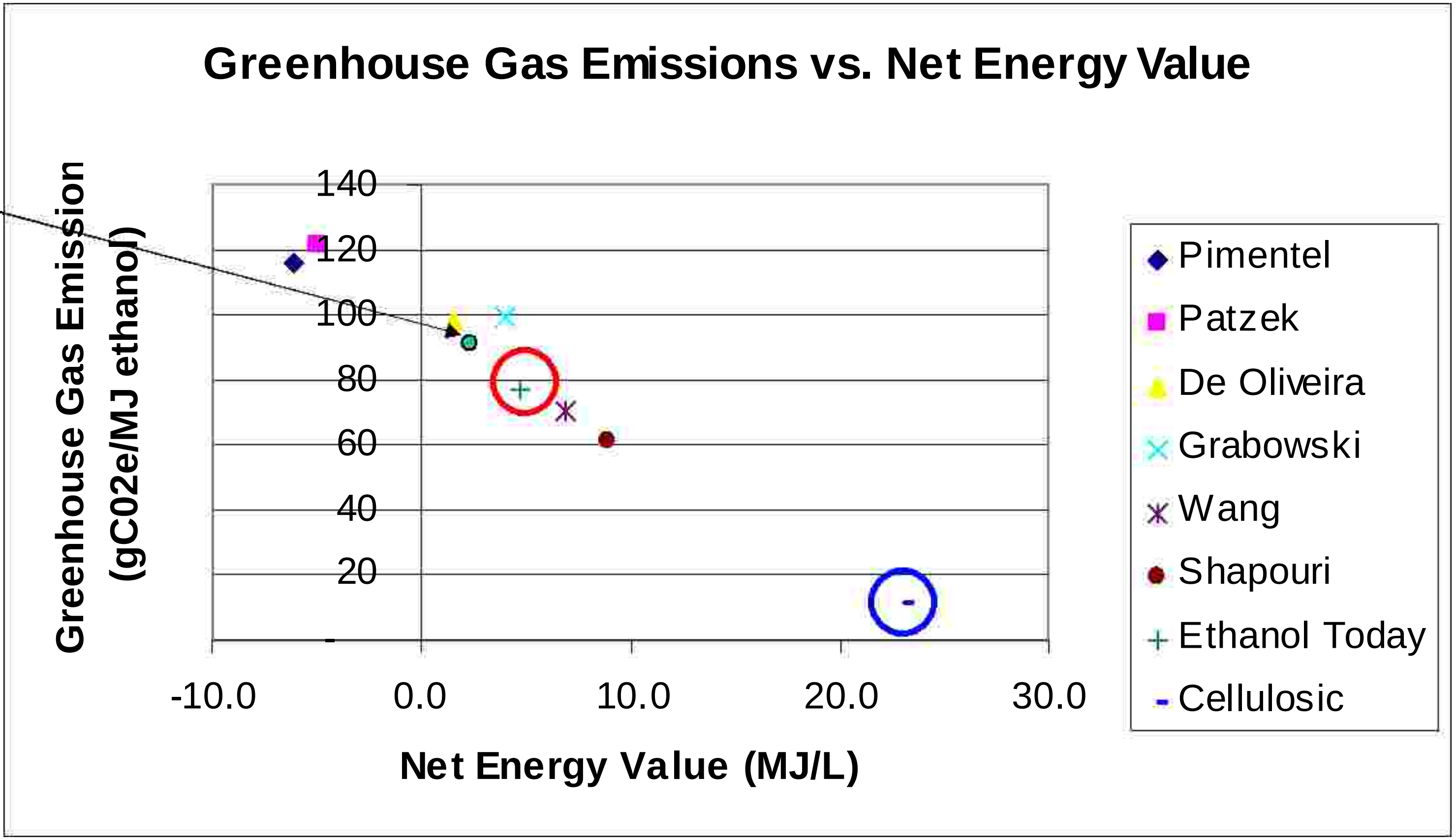
- **Switchgrass used to cover Great Plains**
- **Grows fast; can stand 10ft high**
- **Farmers use it to control erosion**
- **Uses water efficiently**
- **Farrell *et al* calculate:**
  - **Input Energy: 3.2 MJ/L (after accounting for lignin combustion)**
  - **Coproduct Energy 4.8 MJ/L**

Matt Bowen, National Academies Staff Talk, November 14th, 2006

Cellulosic: Greenhouse Gas Emissions vs. Net Energy Value

○ = corn ethanol ○ = cellulosic ethanol

GHG Reference point for gasoline



Matt Bowen, National Academies Staff Talk, November 14th, 2006

Many Issues with Bio-fuels

- Developing the enzymes necessary to do the fermentation
  - Biological research – this is where most of the federal funding is targeted
- Transporting the bio-mass to the fermentation location is expensive
  - High moisture content
  - 2000 tons/day need to be within 20 – 50 miles of the processing facility

Engine Combustion and System Integration Research

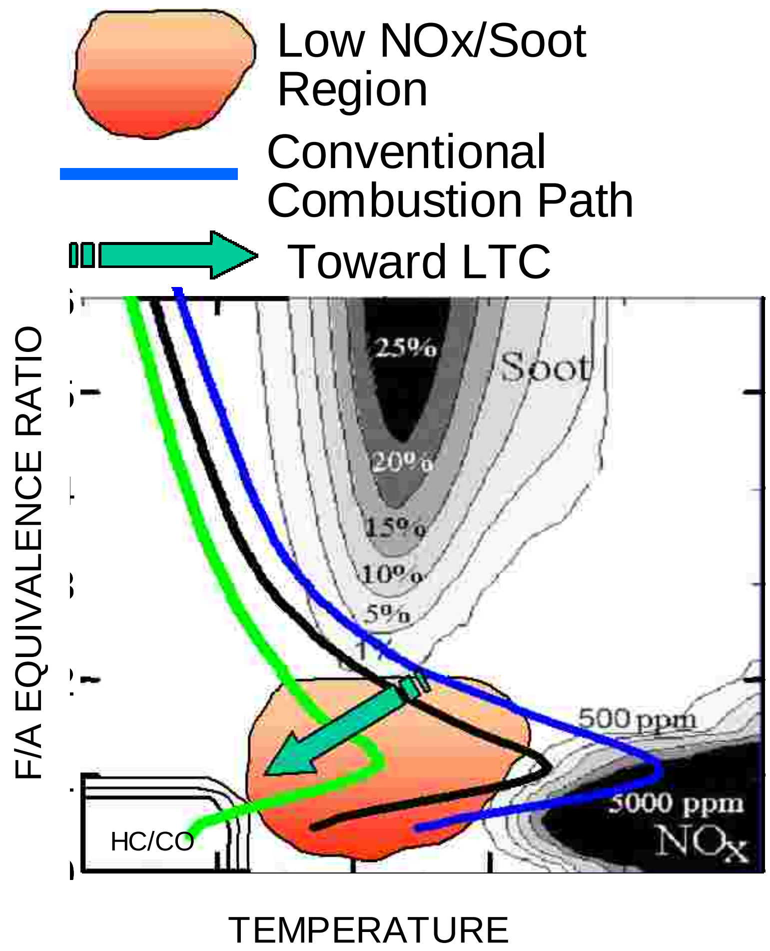
The current emphasis in the US

No Change from Last Year

- More of the same:
  - Low Temperature
    - More acronyms have been added, HECC
  - Improved aftertreatment systems
    - Component development
    - System optimization
  - Renewed interest in scaling results from one engine size to another
- Activities are both experimental and computational
  - Development of capabilities and application to concept systems

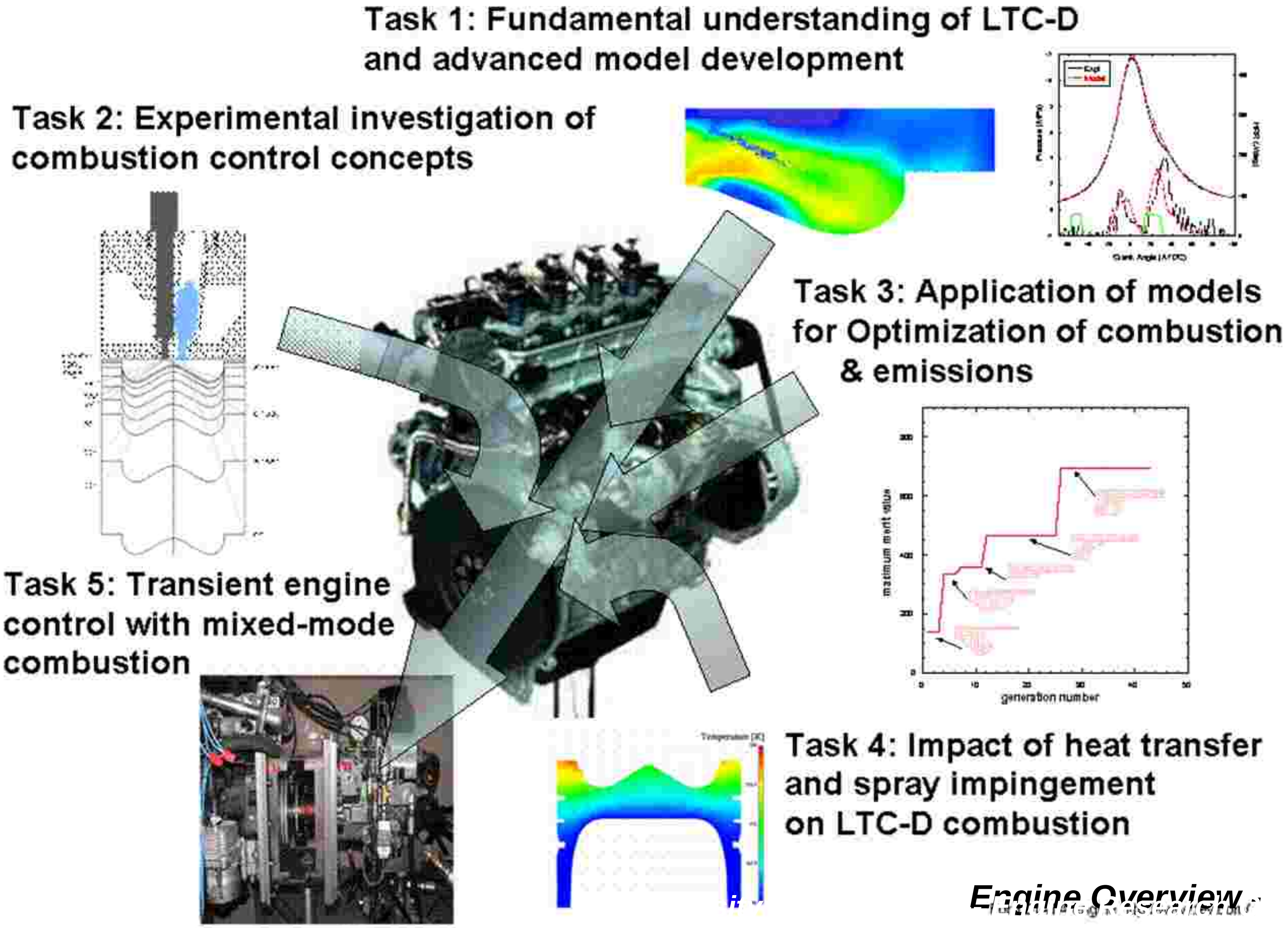
Low-Temperature Combustion (LTC)

- **Critical Issues:**
  - **Practical "windows" can be identified:**
    - **T<2100 K to keep NOx from forming**
    - **T>1500 K to generate sufficient OH to complete oxidation of CO and HC**
  - **Exhaust temperature are low with LTC**
    - **Catalytic clean up of the exhaust may be difficult**
  - **The soot and NOx islands were determined by static calculations of, T = 1.0 ms, P = 6 MPa and EGR = 0% - In reality they move!**

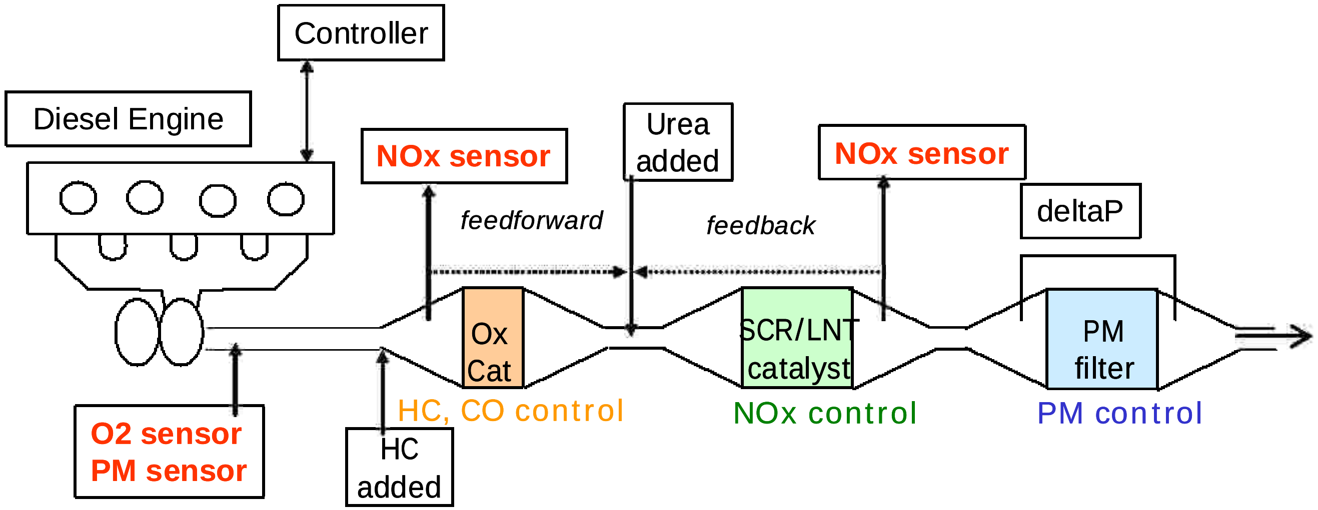


Concept was originally proposed by Kamimoto, SAE 880423

Combustion Optimization and New Combustion Regimes



Powertrain Integration and Total System Optimization



- The aftertreatment system, which is passive, will dictate the engine operating conditions
- Engine needs to supply the exhaust thermodynamic state and composition that is needed for optimum aftertreatment performance at that instant.
- Detailed fundamental understanding of each sub-system will be required

Diesel LTC

Dave Foster, Rolf Reitz, Chris Rutland, Youngchul Ra, Manuel Gonzalez, Roger Krieger, Richard Opat, Ryan Butts

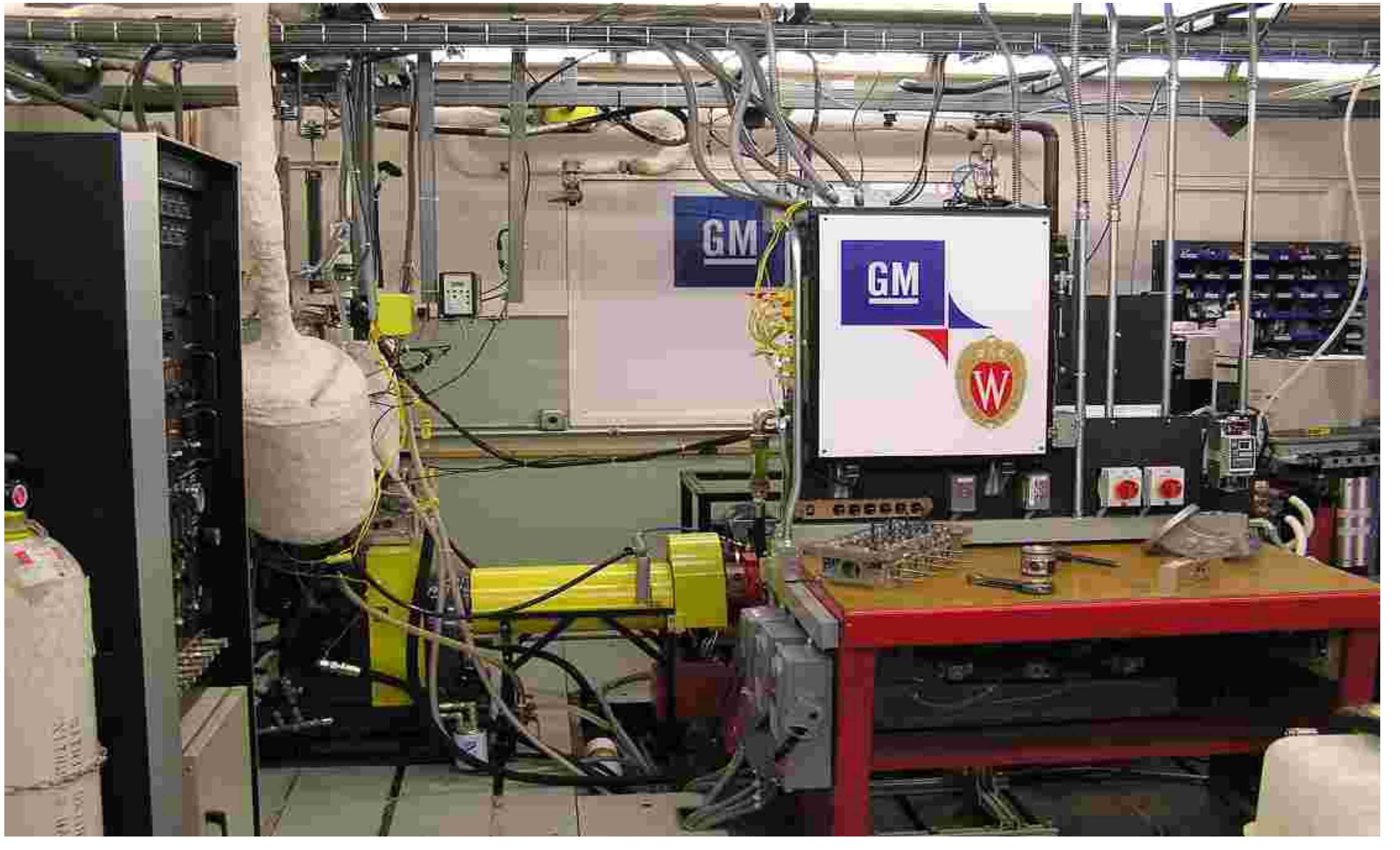
Russ Durrett, Bob Siewert, GM

GM-ERC-CRL, DOE, BP-Amoco

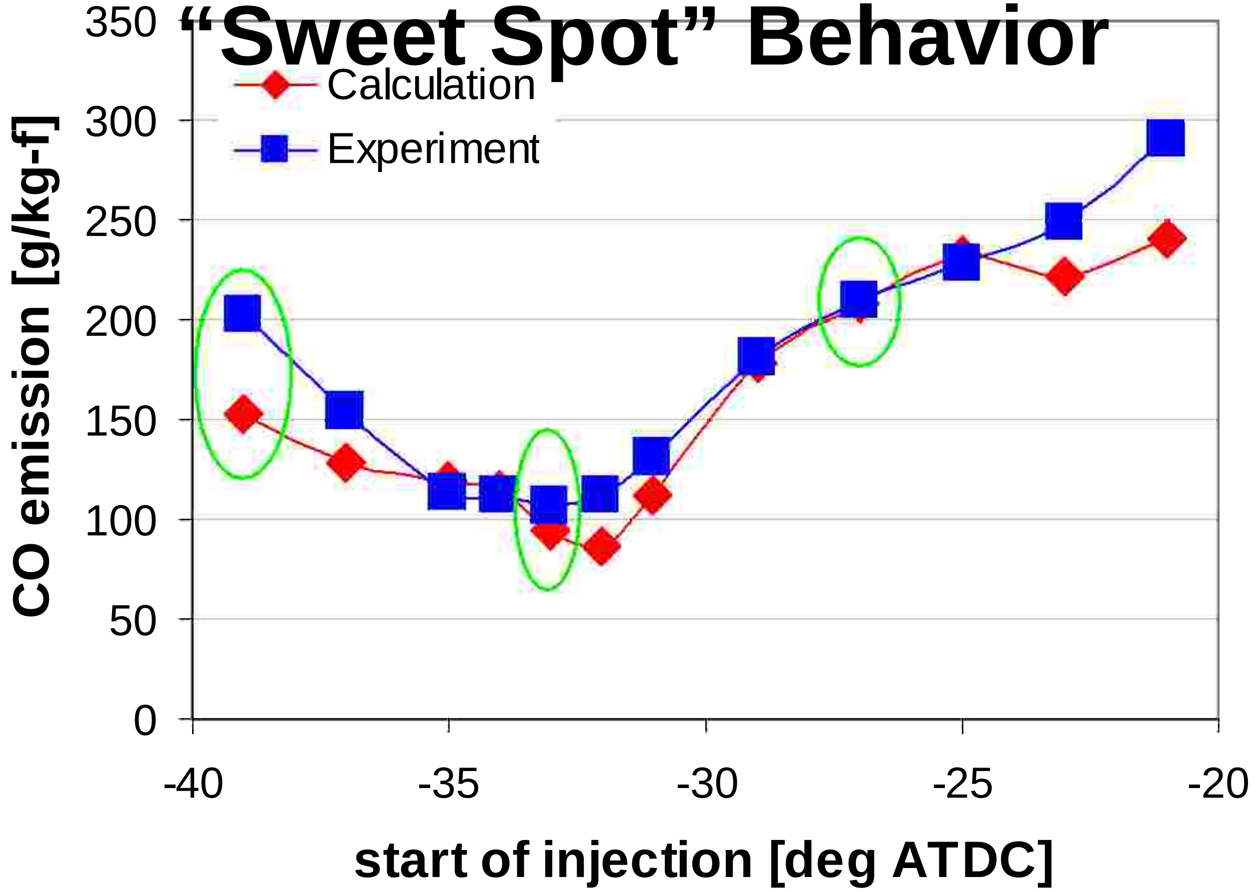
Diesel LTC Single-cylinder Lab

- *Objective: To explore injection, in-cylinder conditions and fuel effects on mixing and combustion regimes in a High Speed DI LTC-D engine*
- *Approach:* To incorporate a study fuel volatility and cetane number effects (focus on properties similar to those of naptha's, light kerosene and cyclo-alkanes) on LTC-D, knowing the non-linear coupling between the ignition kinetics (both two stage and single stage), the temperature and pressure time histories of the cylinder gases and the mixing processes occurring within the cylinder

SCE lab (June ’06)



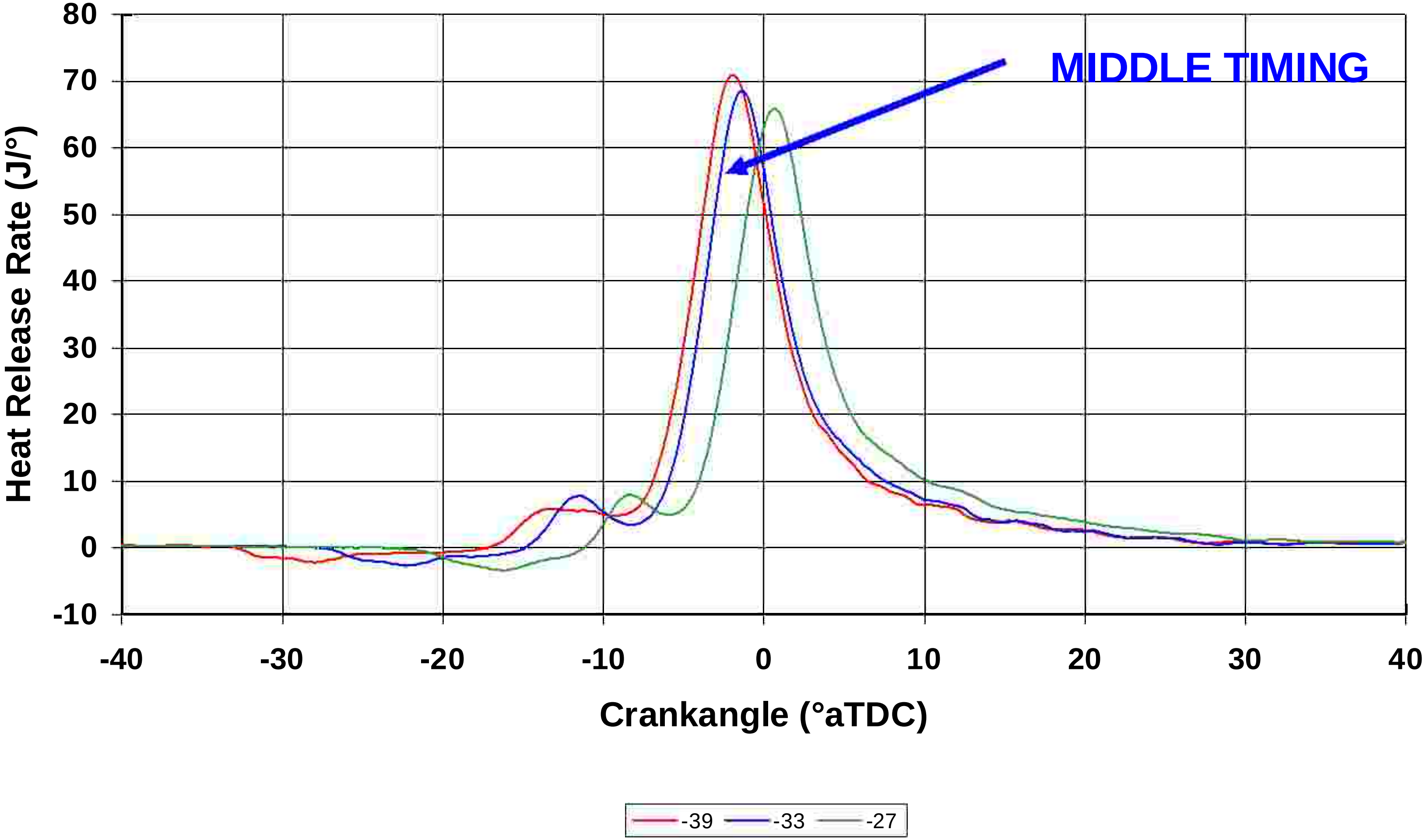
“Sweet Spot” Behavior



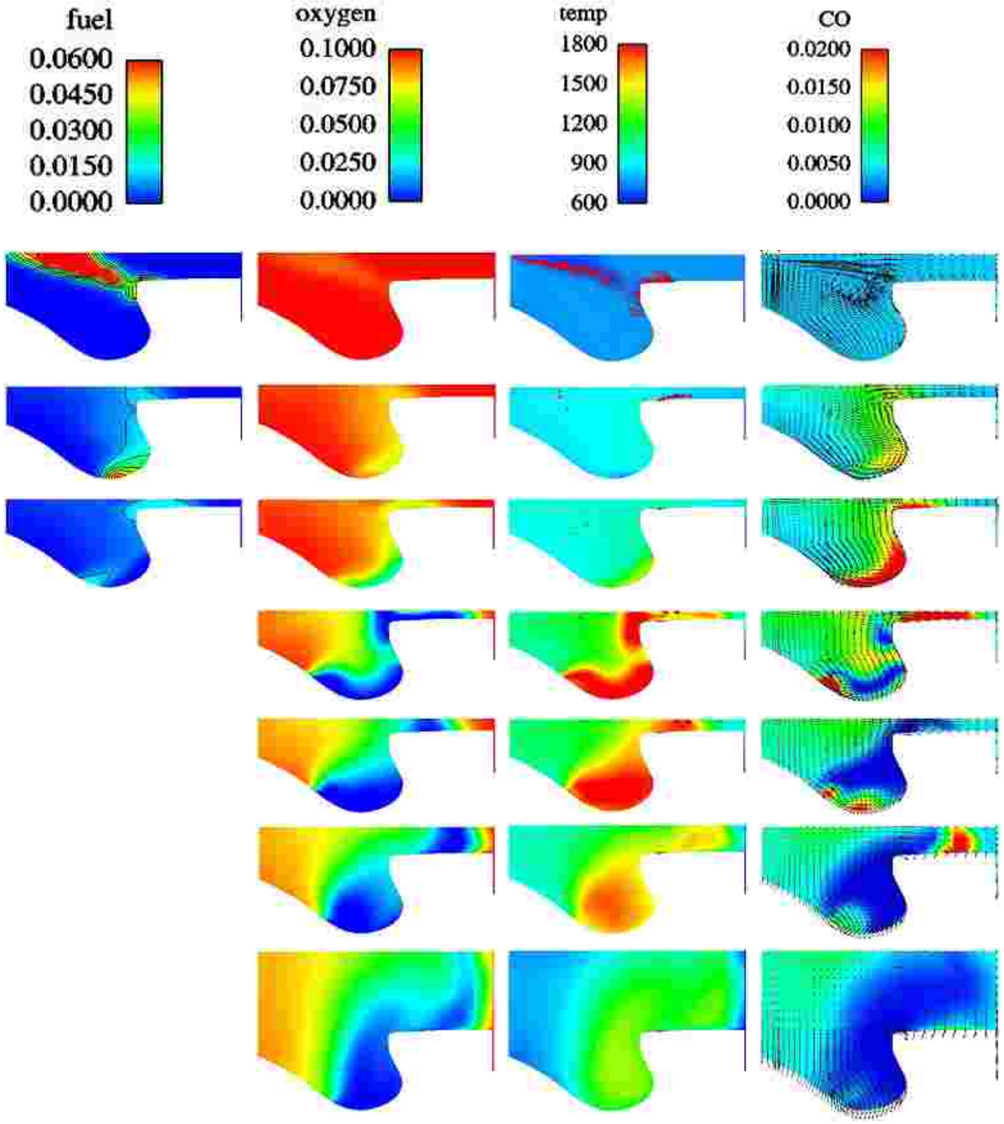
Baseline Conditions, 155º Nozzle with European Fuel; Calculations by Youngchul Ra

"Sweet Spot" Behavior – Middle (Min CO)

Euro Fuel Baseline 155 Degree



“Sweet Spot” Behavior – Middle (Min CO)



- -33º ATDC (-28.2º Actual)
- Spray split between bowl and squish regions
- Late cycle (40º ATDC) shows conversion of squish CO
- Generated mixing seems to create two combustion regions
- Effective use of available O_2 available in the cylinder

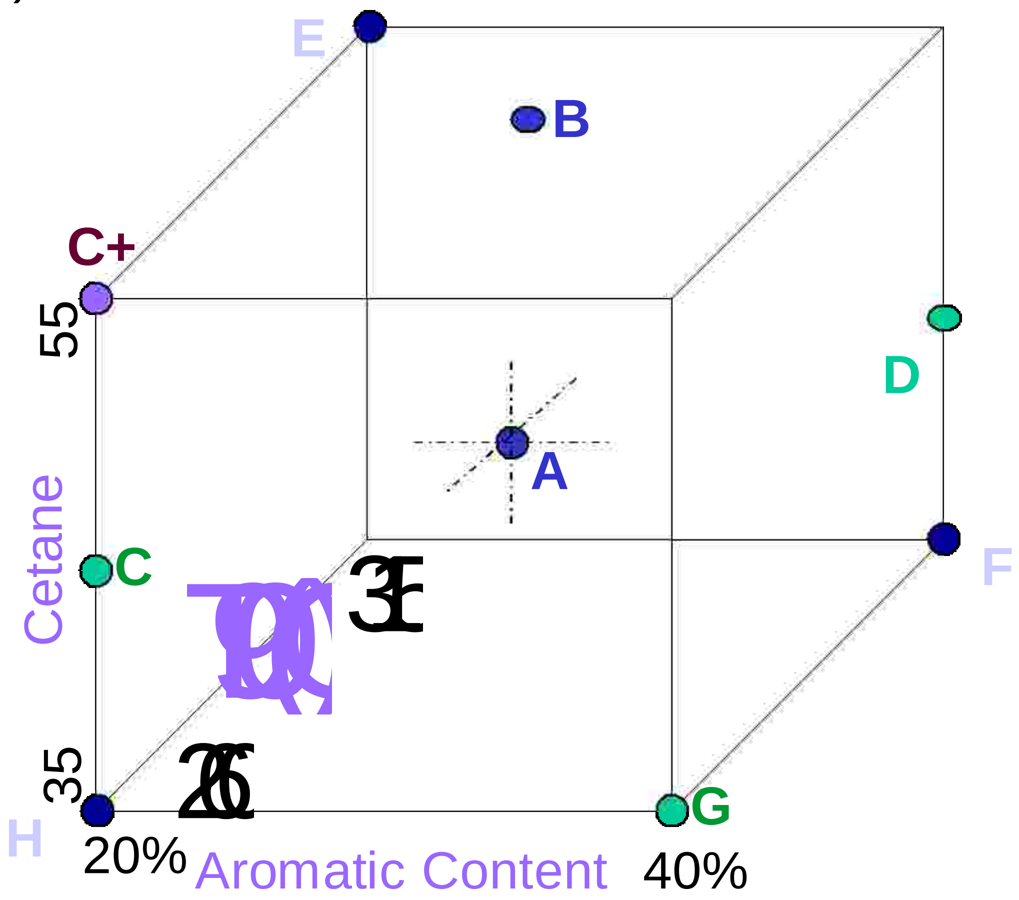
“Sweet Spot” Behavior – General

- Variation of the injection timing creates an optimal split of fuel into the bowl and squish regions
- Early and late timings cause isolated small scale mixing systems that poorly utilize the available O_2 (~10% excess of stoichiometric)
- By creating a mixing scenario that best utilizes the available in cylinder O_2, minimization of CO can be realized through co-location with O_2

Current Fuels and Blend Proposal for LTC

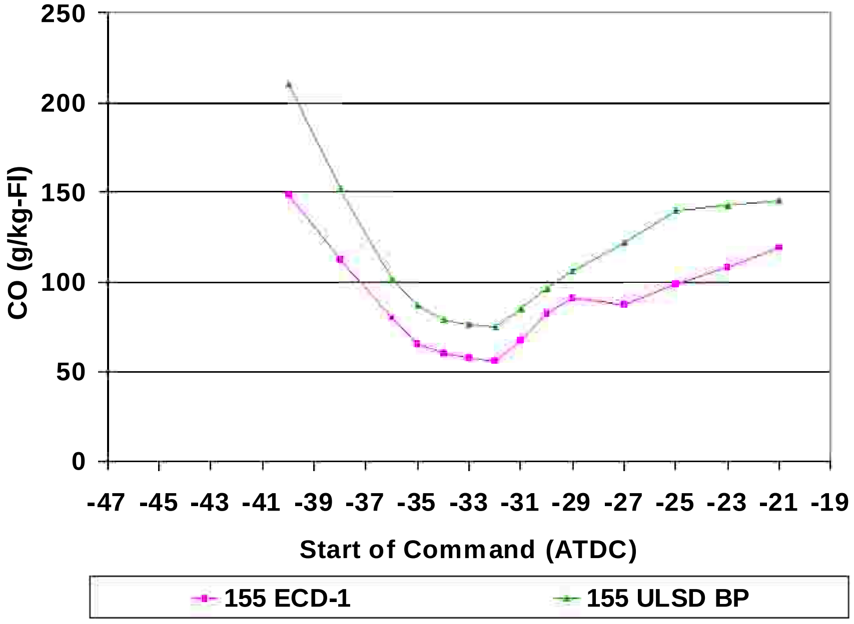
A: reference fuel (BP-ULSD)
26/44/295
B: ECD-1:25/50/317

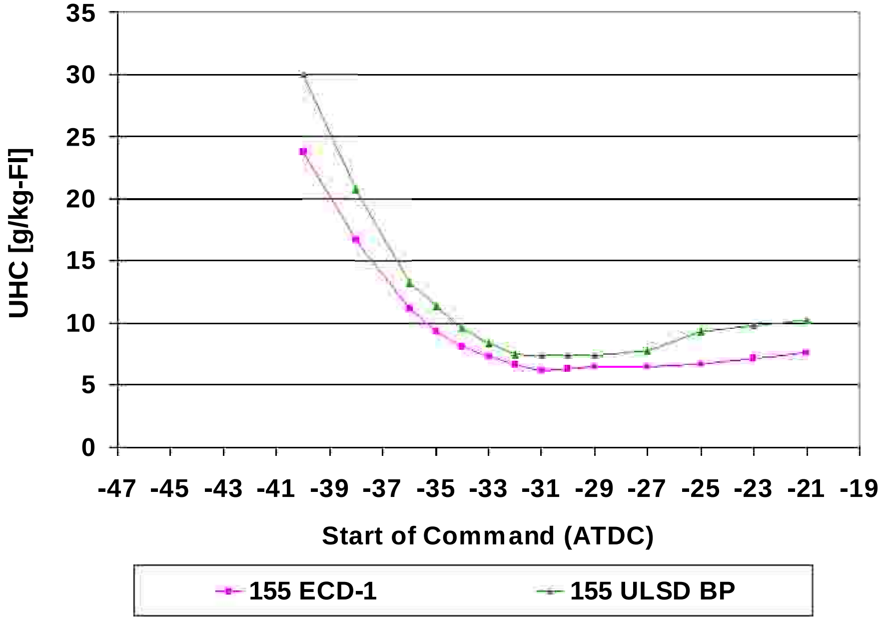
C: 20/45/260
D: 40/45/315
G: 40/35/260
C+:20/55/260
E: 20/55/315
F: 40/35/315
H: 20/35/260



Analysis of Current Data

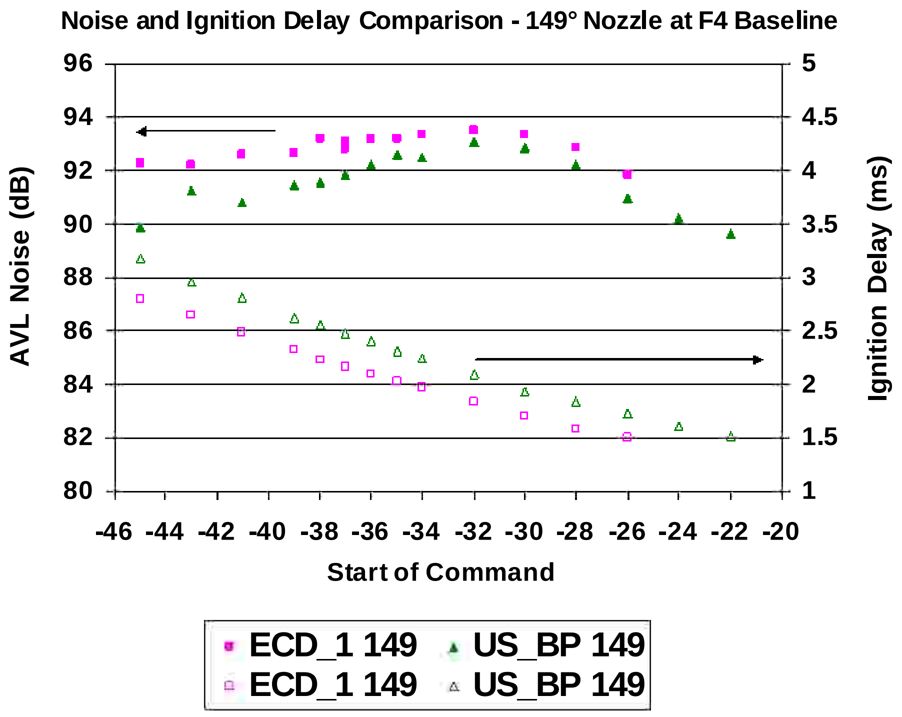
Fuel Effects with US “Narrow Cut” Removed

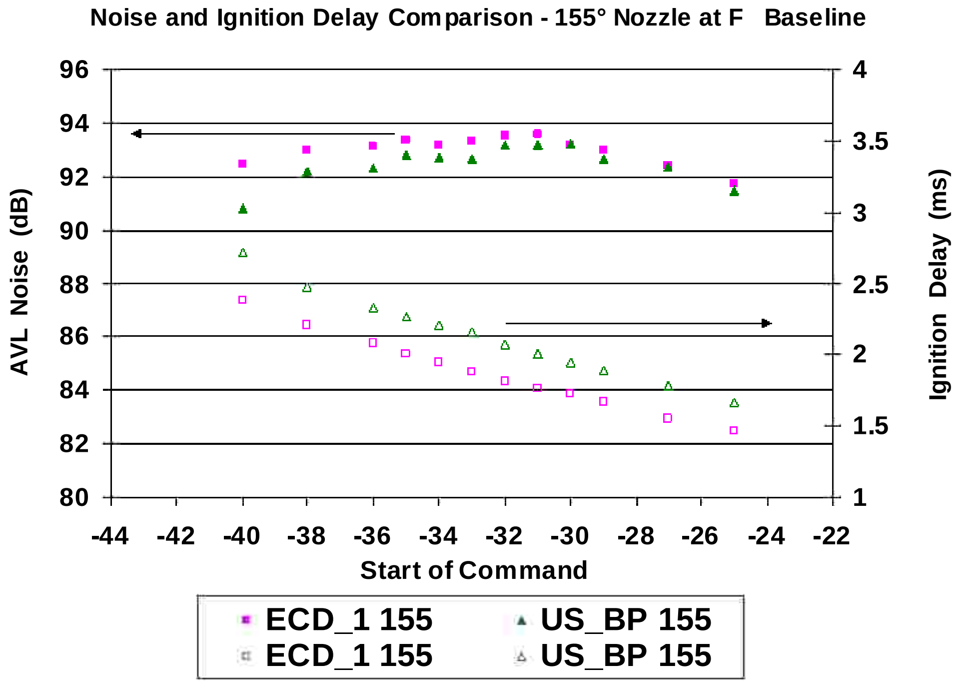




- ECD-1 clearly shows lower CO/HC levels for a wide range of injection timings
- Effects of these fuels on large scale trends is still unclear
- A slight widening of the CO sweep spot and UHC curve *may* occur with ECD-1

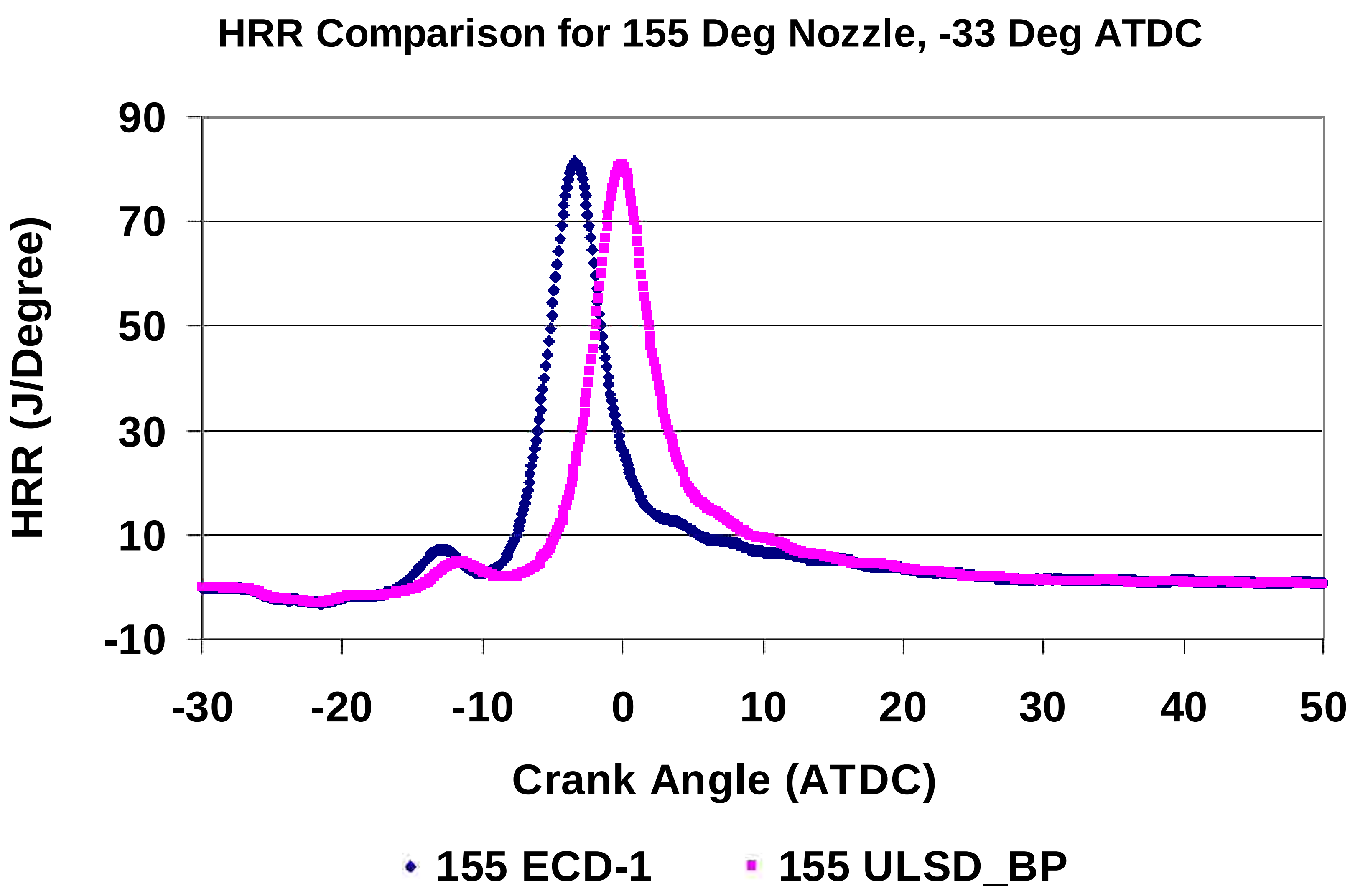
Analysis of Current Data





- ECD-1 fuel shows generally both higher noise and lower ignition delay for all nozzle angles

Analysis of Current Data



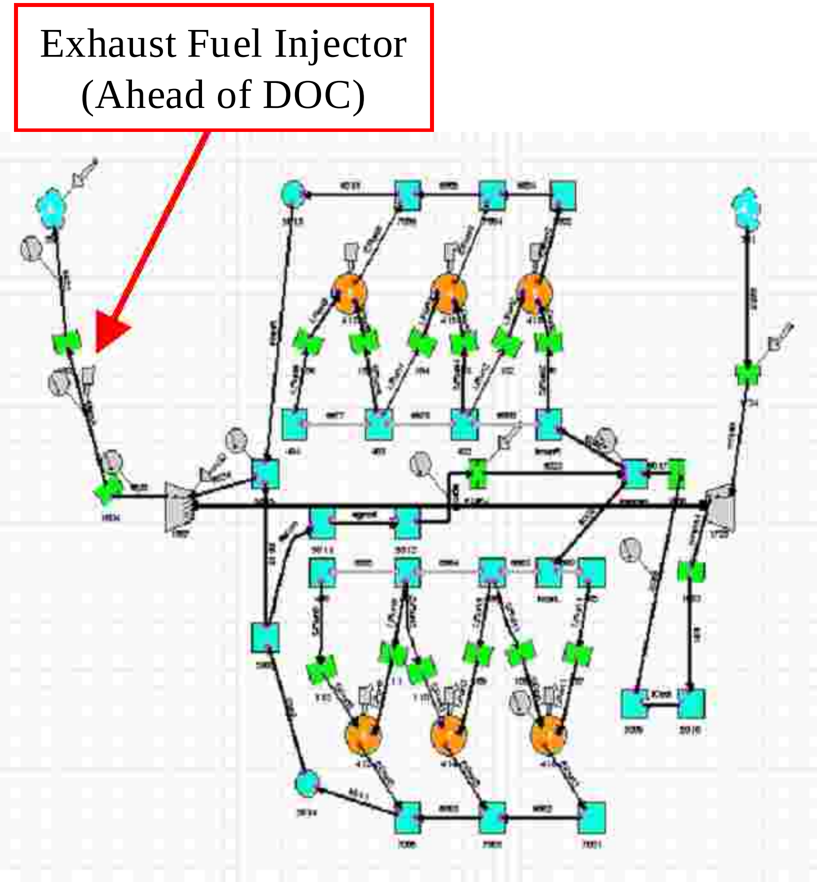
Aftertreatment System Modeling

Researchers involved: **Professors: Rutland and Foster GM: He**
Students: England, Bagal, Strzelec, Singh

Objectives:

- **Develop an integrated system level computer model to s mulate the interaction of diesel engines and aftertreatment devices**
- **Develop and test component models**
  - **Engine**
  - **Emissions (soot, NOx, CO, HC)**
  - **DOC**
  - **DPF**
  - **DPF/LNT**
  - **SCR**
- **Use the model to:**
  - **Examine device interactions (steady state and transient operation)**
  - **Investigate the effect of DPF loading and regeneration on engine operation**
  - **Model and compare different DPF regeneration techniques**
  - **Model prevention and control of runaway DPF regenerations**
  - **……**

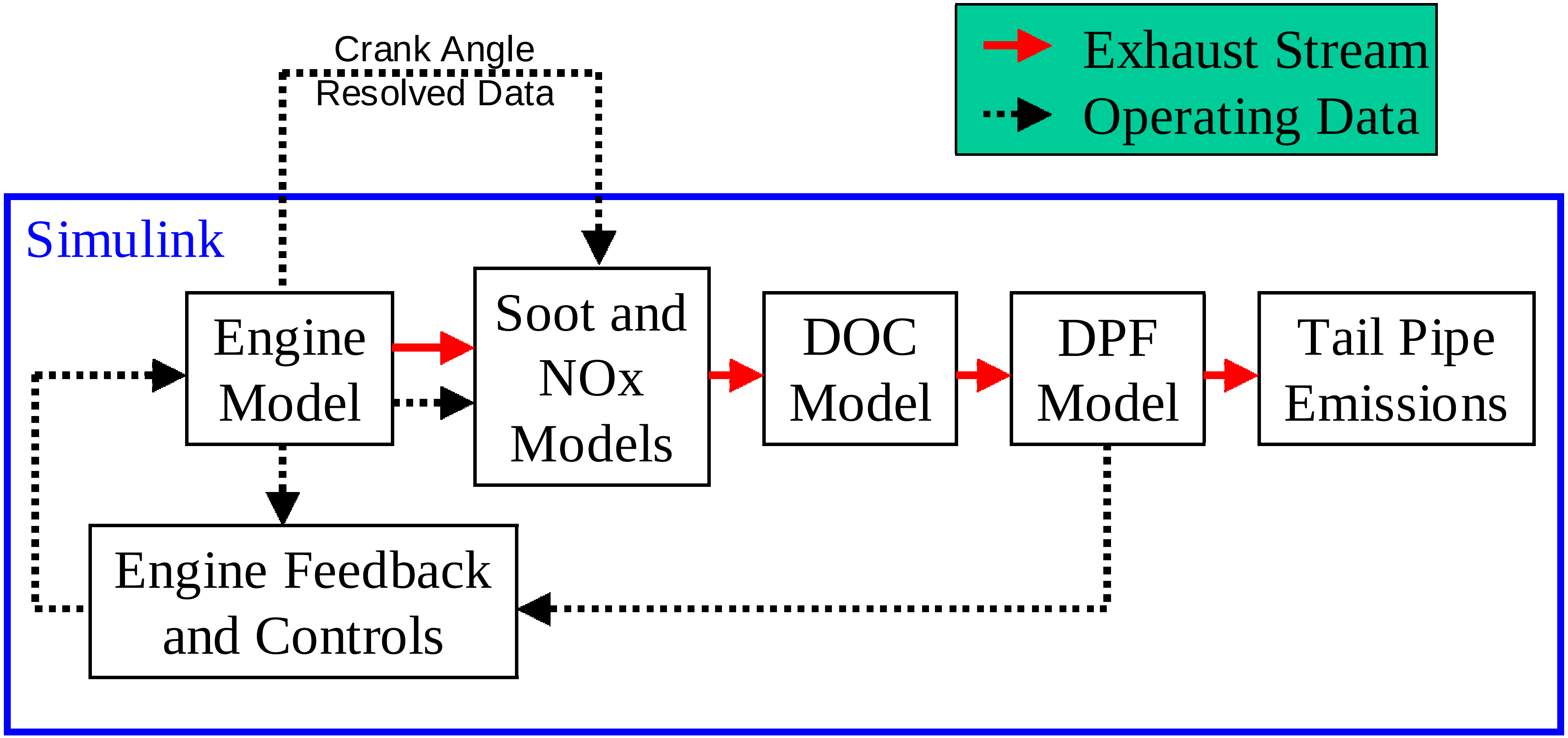
Diesel Engine Model



Example of a WAVE engine model with sensors and actuators

- **WAVE, one dimensional engine simulation software, is used**
  - **Includes:**
    - **Heat transfer model**
    - **Flow model**
    - **Turbocharger model (VGT)**
      - **Turbine and compressor maps**
      - **External PI rack controller implemented in Simulink**
    - **Combustion model**
      - **Heat release rates extracted from experimental cylinder pressure traces**
      - **Could also use Wiebe model in WAVE**
  - **Calibration done using results of experimental study conducted by General Motors researchers**
  - **Communicates with Simulink using sensors and actuators**

The Integrated Model



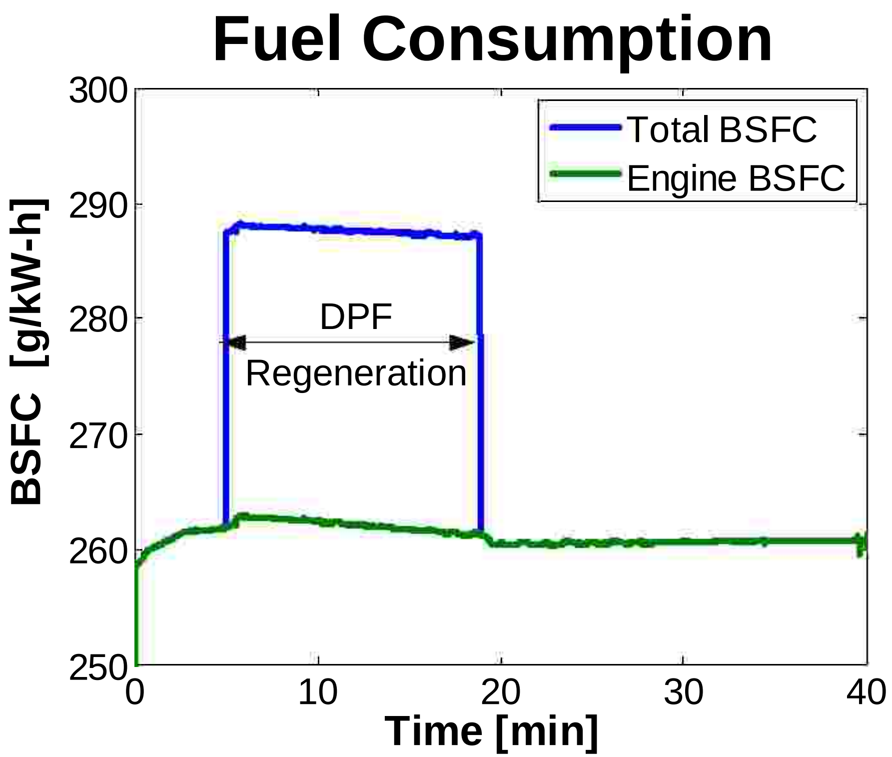
Schematic of the Integrated Model

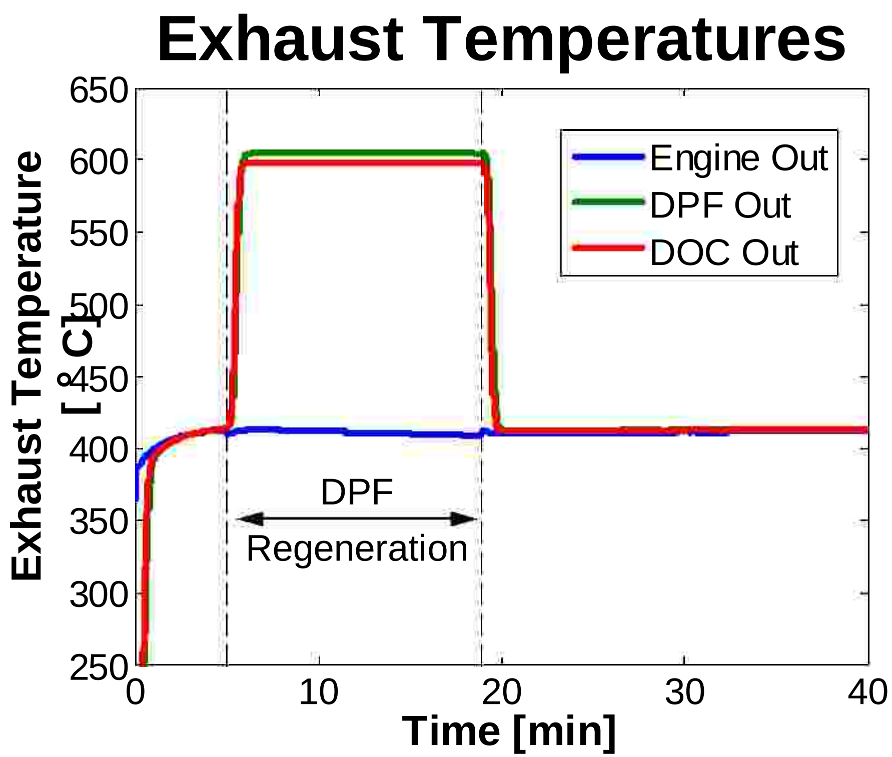
Testing the Model

- **The component models have been previously tested and validated**

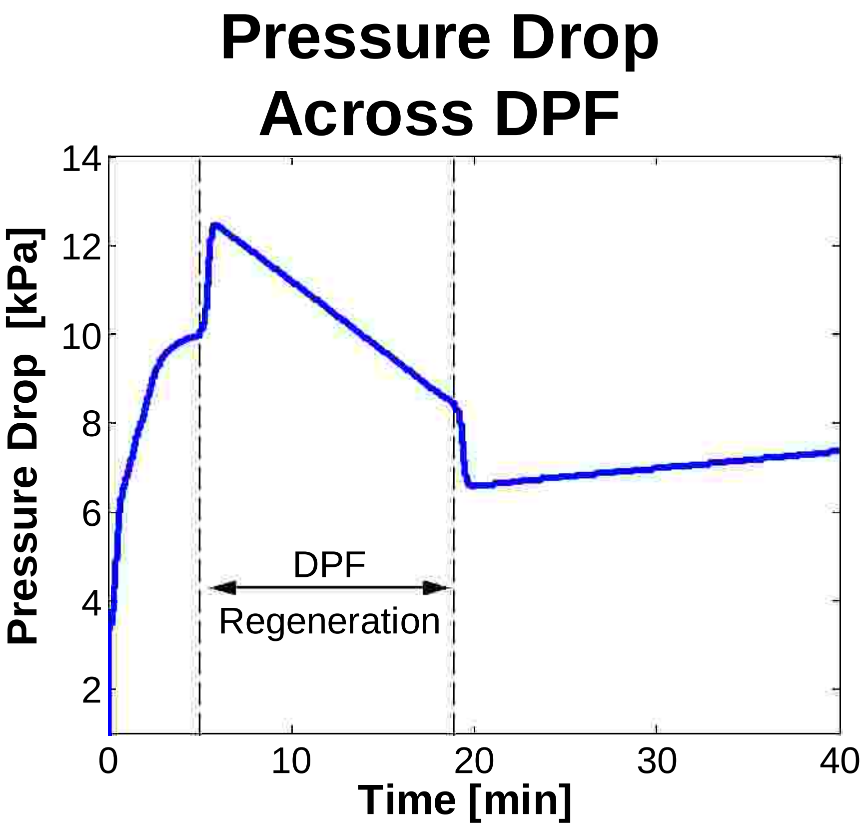
- **The integrated model needs to be tested to verify proper component interaction**
  - **DPF loading and regeneration simulations have been done to test the model and component interaction**
  - **The simulation results are consistent with experimental results presented by Singh et. al. (SAE 2006-01-0879)**

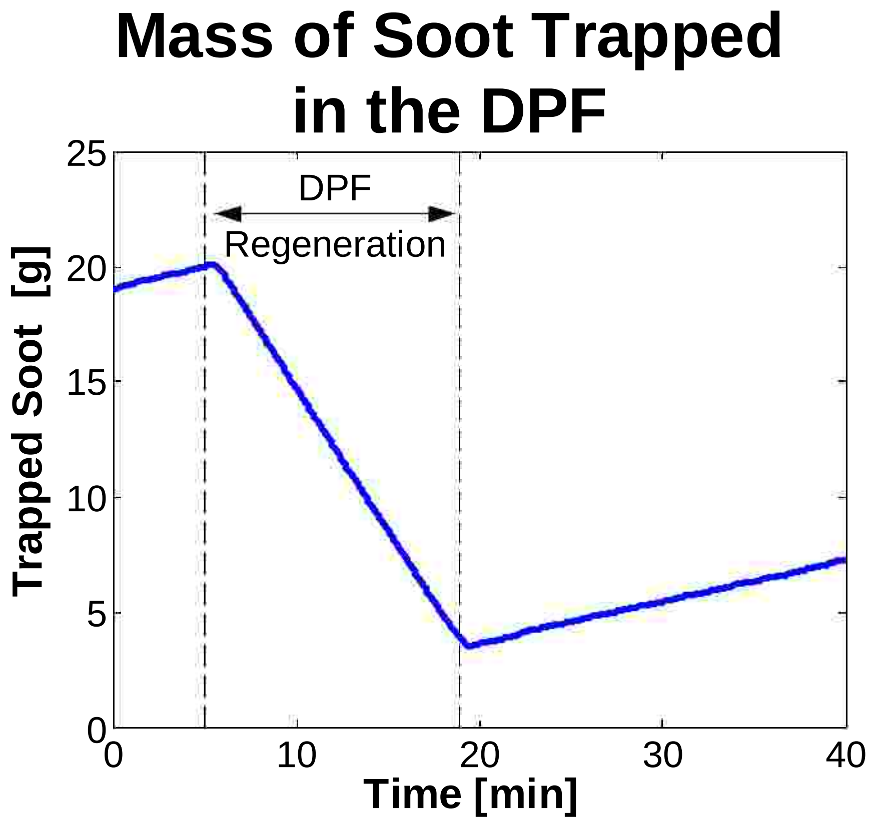
DPF Regeneration (Mode 5)



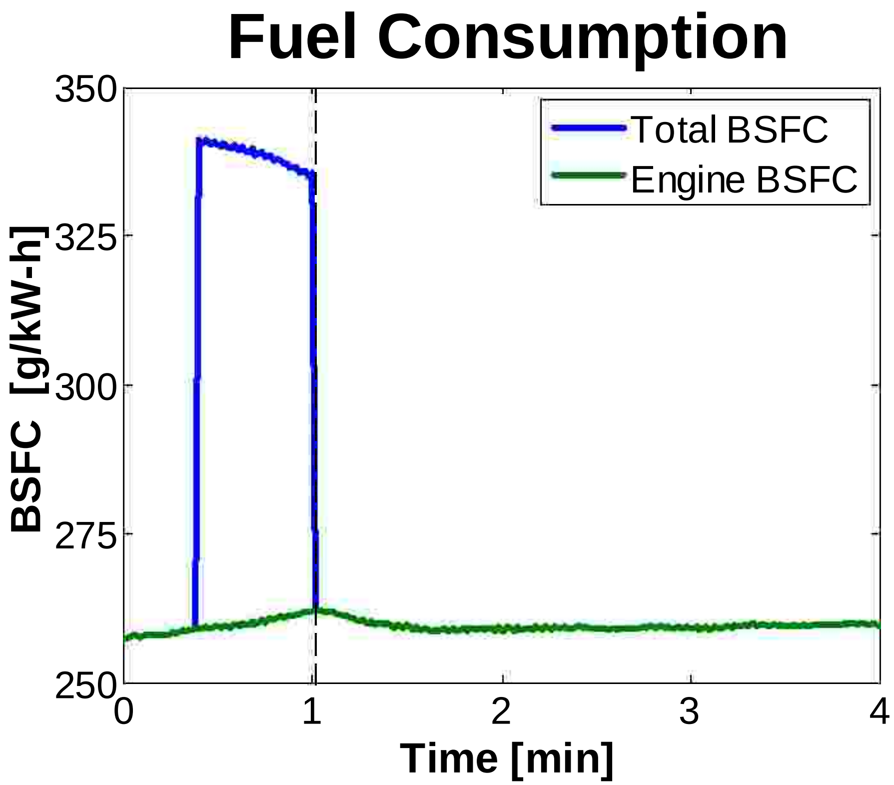


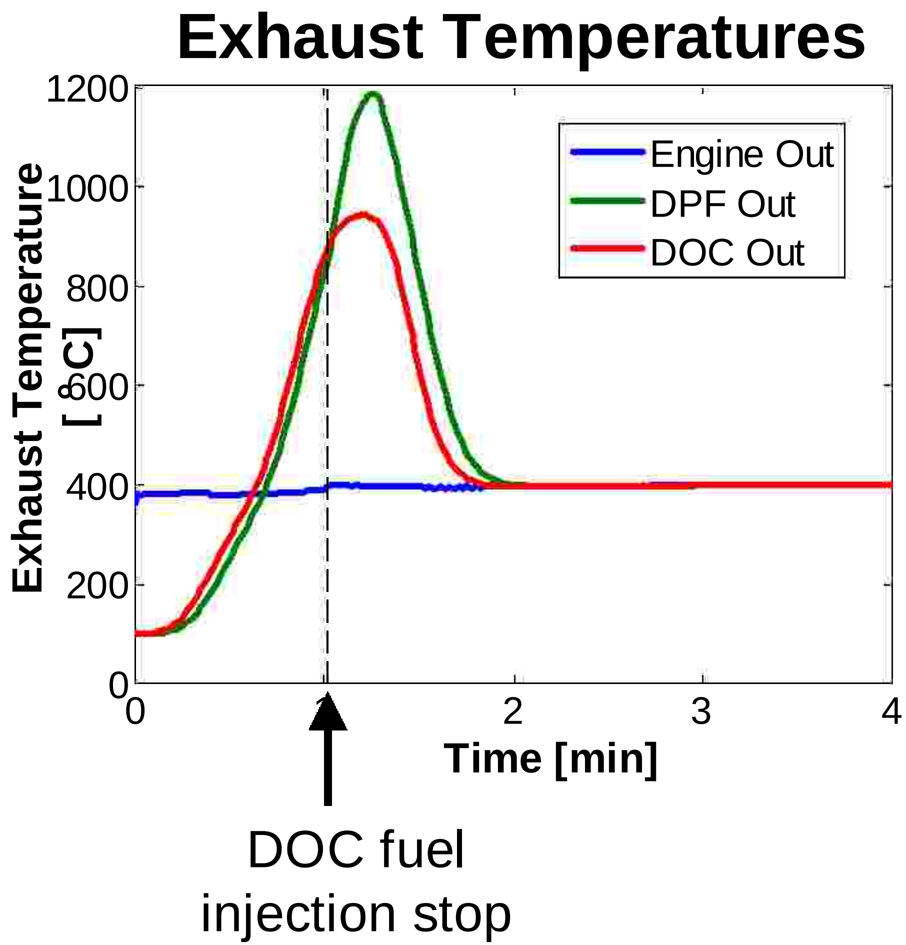
DPF Regeneration (Mode 5)





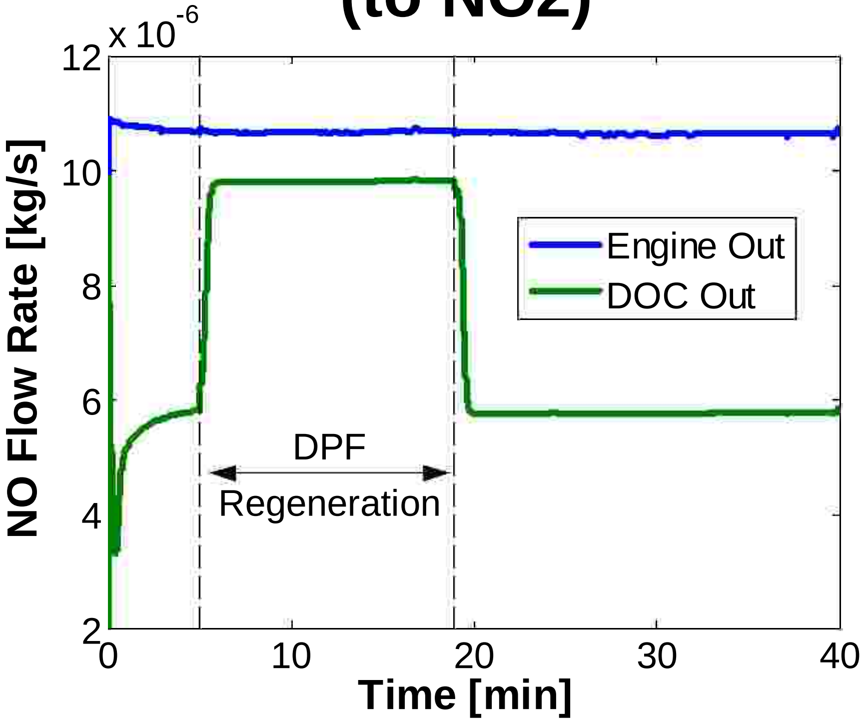
Runaway Regeneration (Mode 5)





DPF Regeneration (Mode 5)

DOC NO Oxidation (to NO2)

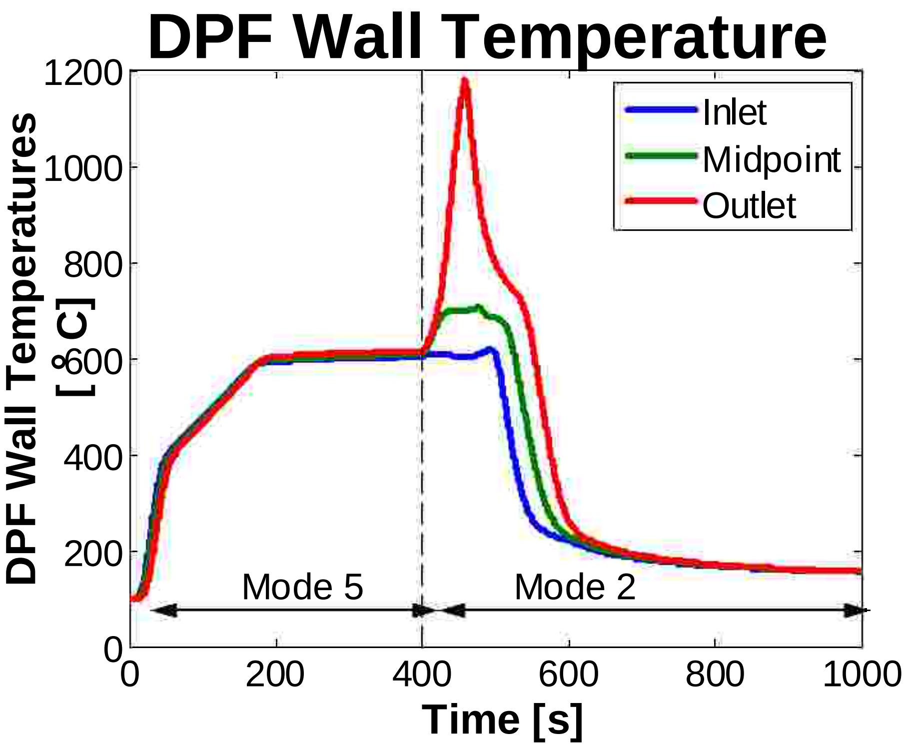


Summary

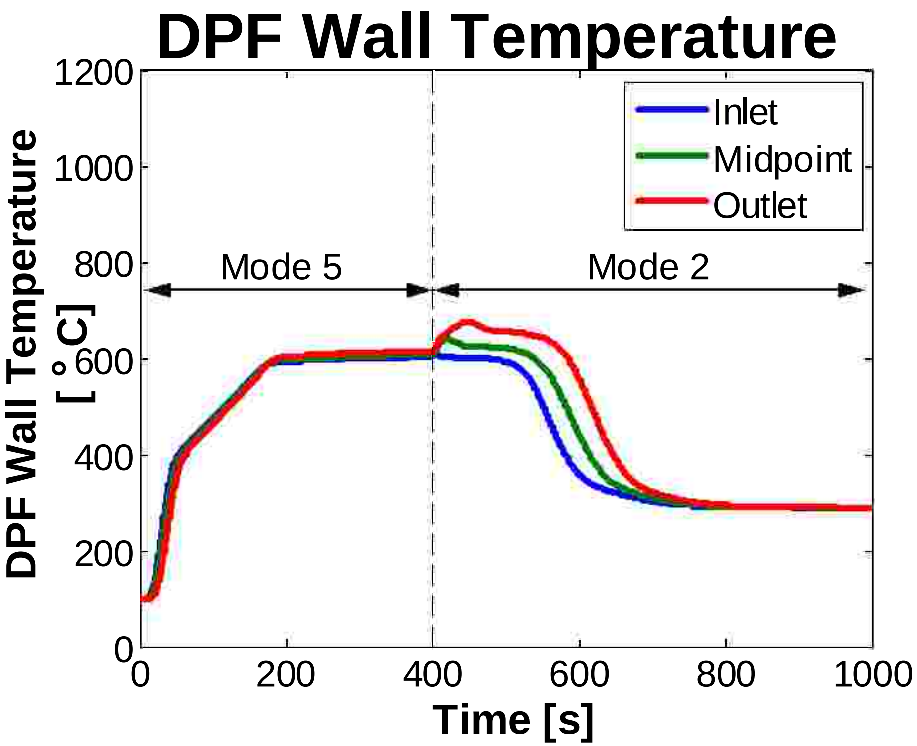
- The fuel injected ahead of the DOC was controlled to achieve a desired DPF inlet temperature of 600 [° C]
- Simulation results are consistent with the experimental results given by Singh et. al. (SAE 2006-01-0879)
- Regeneration was set to start at a soot loading of 20 [g] (3.2 [g/l]) and stop when the loading dropped to 4 [g] (0.6 [g/l])

Engine load transients during regeneration (mode 5 to 2)

Regeneration: Runaway after Mode Switch

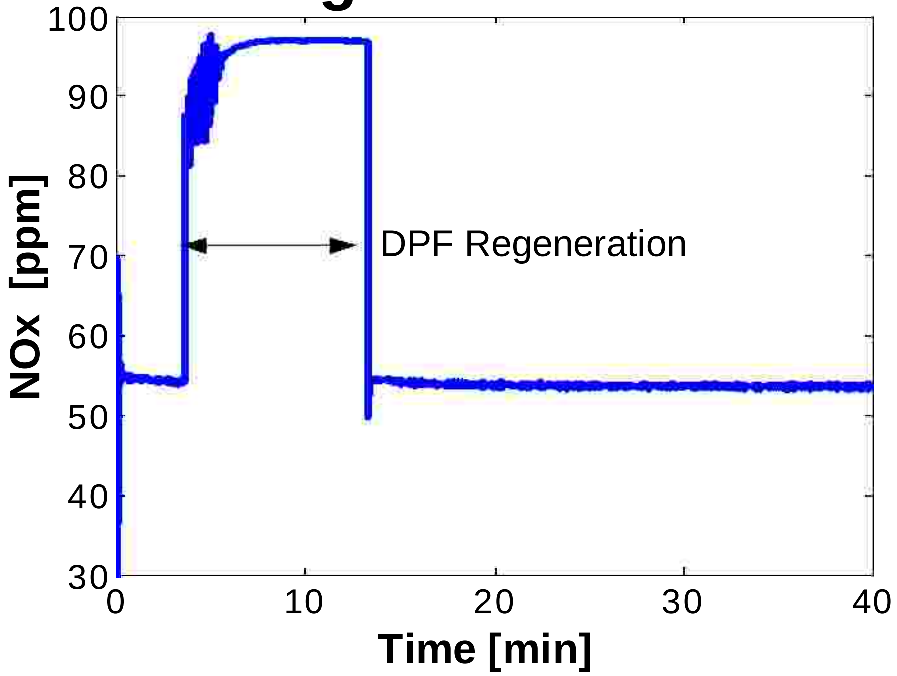


Prevent Runaway with Intake Throttling



Throttle Assisted Regeneration (Mode 3)

Engine-Out NOx

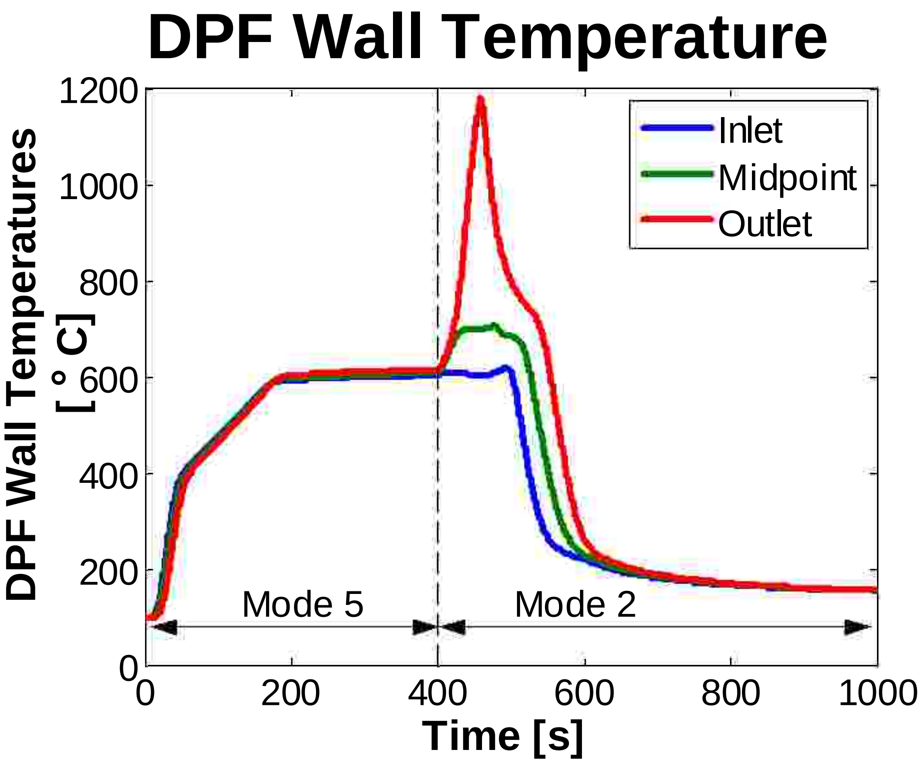


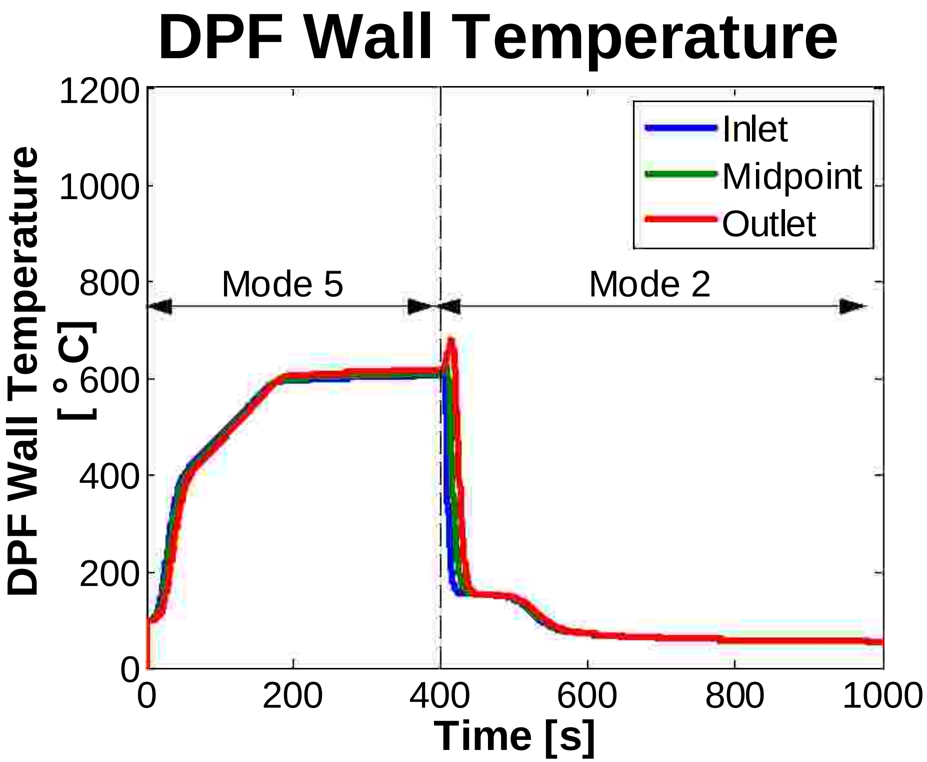
Summary

- DOC exhaust inlet temperatures too low for exhaust fuel injection (DOC inlet temperature should be above ~300 [° C])
- Intake throttling increased the exhaust temperature from 276 [° C] to a target value of 320 [° C] (DT = 44 [° C])
  - Greater DT's are possible
- Intake throttling was successfully used to enable DPF regeneration by increasing the exhaust temperature enough to allow for exhaust fuel injection
- Increased NOx during throttling was a result of reducing the EGR too much

Engine load transients during regeneration (mode 5 to 2)

Regeneration: Runaway after Mode Switch	Prevent Runaway with Air Injection into DPF





Closure

- Fuel diversity has become a focus within the US
  - Diversity of supply
  - Fuel economy
  - CO_2 reduction
- Bio-fuels are expected to play an important role in the fuel diversity portfolio
- Fundamental combustion studies are necessary for continued improvement of the IC Engine powerplants for our mobility systems
  - Reduced life cycle impact
    - Fuel consumption reduction
    - Minimizing environmental impact
    - Reduced total carbon emissions
  - Fuel characteristics will be an important aspect of solving these challenging issues