Combustion Technologies, Aftertreatment Systems and Alternative Energy Carriers for a Carbon Constrained World

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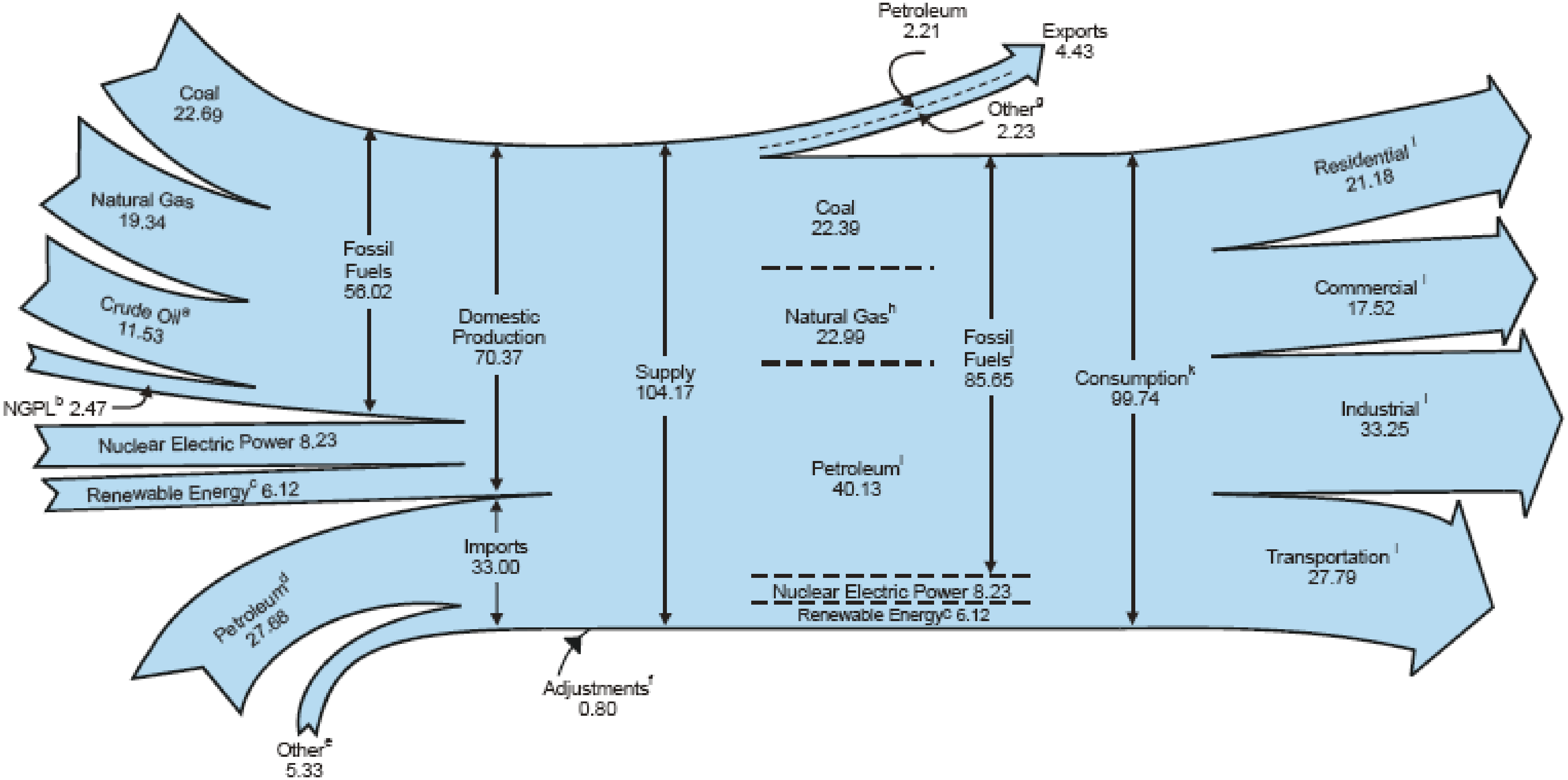
ASME ICE Conference, May 4, 2009

Outline

- Energy Situation Rant
  - Overview, snapshot, of Energy and Mobility Situation
- Drivers and constraints for IC Engine based systems
  - Consideration of alternative fuels and powertrains
- My assessment of the fate of the IC Engine
- Fundamental needs for future power generation systems
- Closure

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.

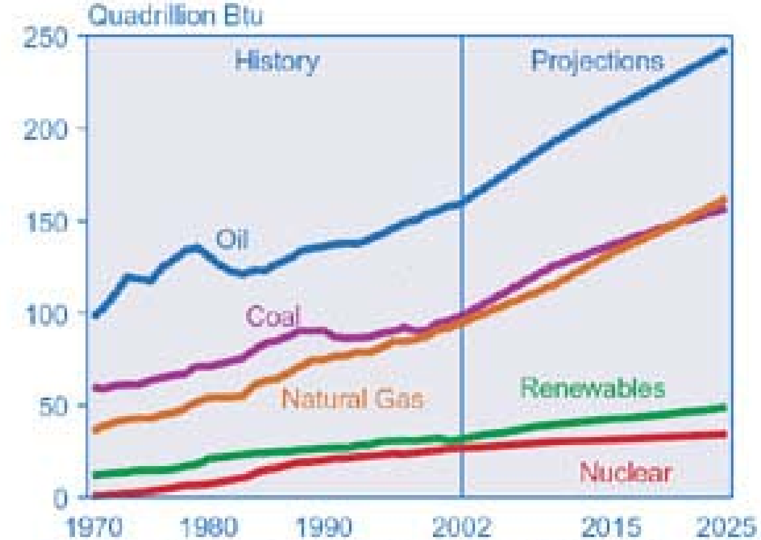
Energy Information Administration / Annual Energy Review 2004

World View of Energy “Consumption”

Figure 7. World Marketed Energy Consumption, 1970-2025

Sources: **History:** Energy Information Administration (EIA), *International Energy Annual 2002*, DOE/EIA-0219(2002) (Washington, DC, March 2004), web site www.eia.doe.gov/iea/. **Projections:** EIA, System for the Analysis of Global Energy Markets (2005).

Figure 10. World Marketed Energy Use by Fuel Type, 1970-2025



Sources: **History:** Energy Information Administration (EIA), *International Energy Annual 2002*, DOE/EIA-0219(2002) (Washington, DC, March 2004), web site www.eia.doe.gov/iea/. **Projections:** EIA, System for the Analysis of Global Energy Markets (2005).

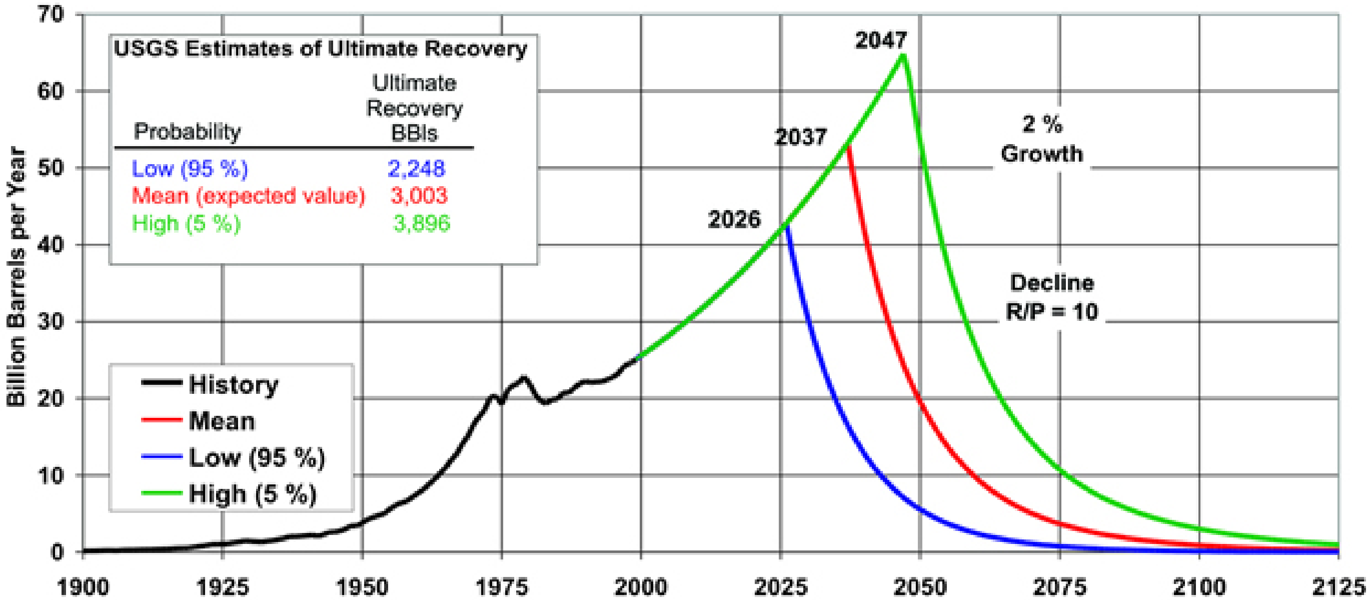
Meeting Projected Energy Demand?

- Ghawar, Abqaiq, Shaybah, Zuluf – Saudi Arabia's four major oil fields
  - Responsible for approximately 80% of Saudi Arabia's oil production
  - Ghawar is responsible for approximately 60% of Saudi Arabia's production
  - Ghawar (1948), Abqaiq (1940), Shaybah (1975) and Zuluf (1965) are all using teriary recovery techniques

Ref: Matthew Simmons, "Twilight in the Desert"

What About Supply? (Hubbert?)

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

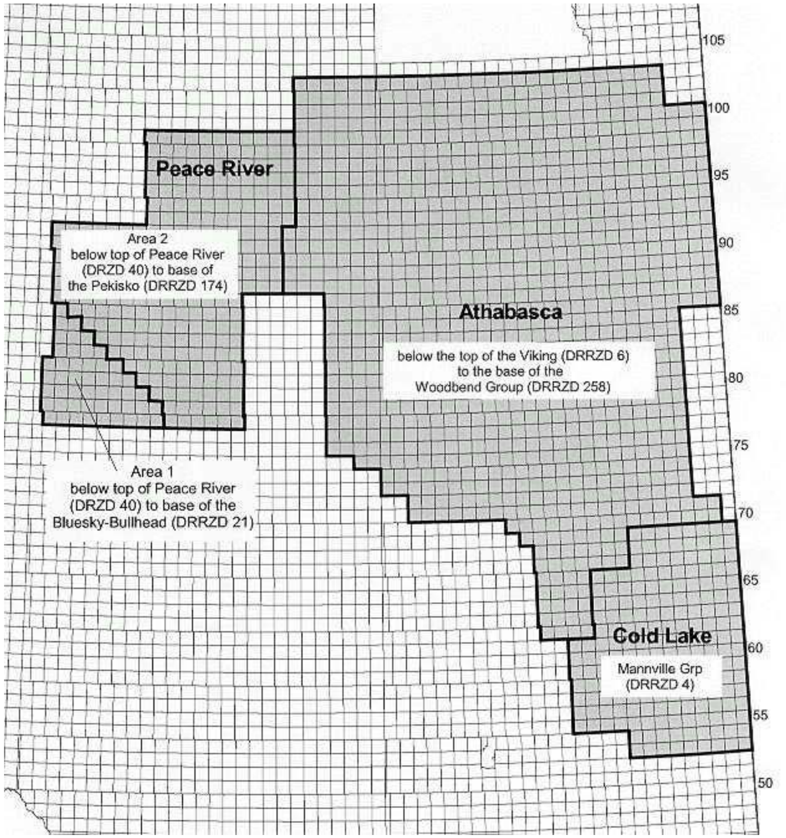


Source: Energy Information Administration
Note: U.S. volumes were added to the USGS foreign volumes to obtain world totals.

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/

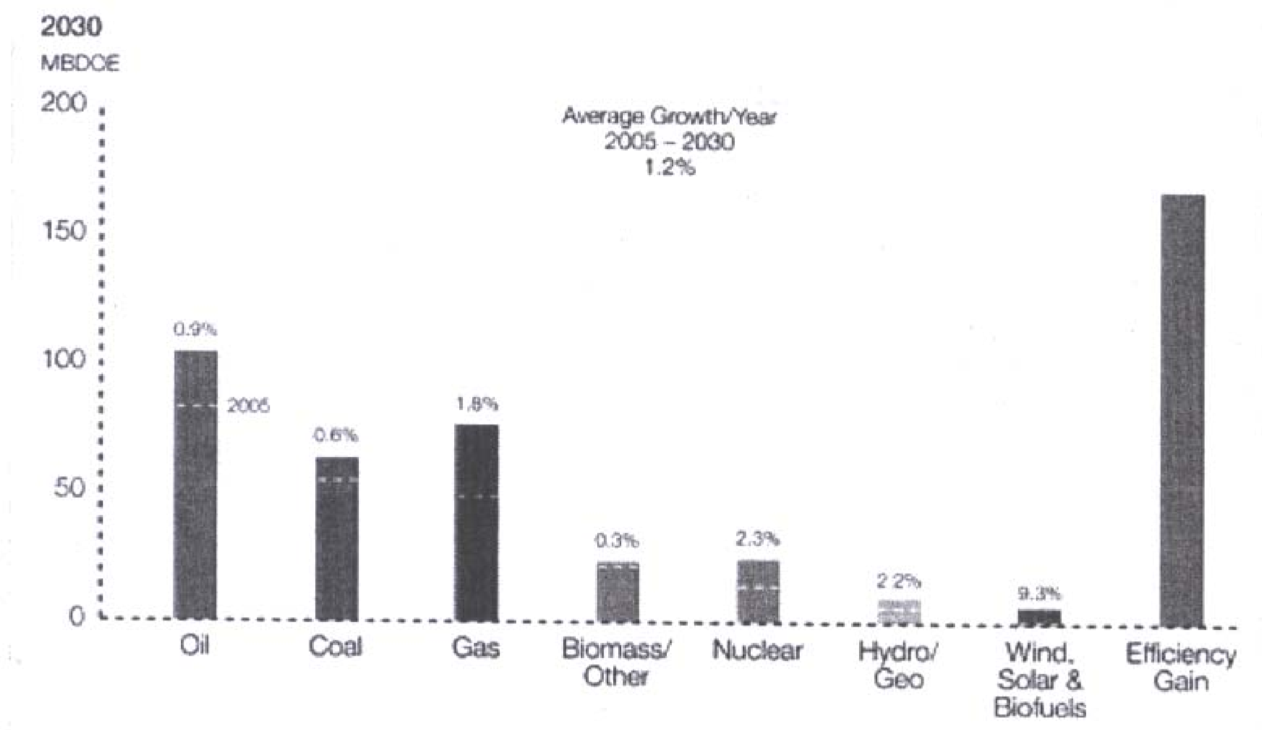
Is Supply Really an Issue?

- As demand for oil increases, its price will increase
  - More challenging reserves become economically viable – ex. Gulf of Mexico, ocean off Brazil
- Alternatives, unconventional “oil”, 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

Is Carbon Really and Issue?

- Personally I think it is, but I also believe it is an relevant question
  - Geological chronologies are often couched in terms of a carbon cycle
  - In my mind there is no question that humans are accelerating the carbon cycle
- HC's are the most precious energy carrier that exist
  - The petroleum used in one year took 875K years to produce
- We should do everything possible to conserve and preserve these precious resources
  - Don't use HC energy carriers for applications where other energy carriers will also suffice
- It is also an irrelevant question because it appears that it will be legislated

Efficiency Gain is a Resource*



- To meet projected energy demands we will need to develop all economic energy sources
- Through 2030 the amount of energy saved through efficiency gains worldwide could be equivalent to 170 M bbl/day

*** Courtesy of ExxonMobil**

Reducing Energy "Use" and Carbon Emissions

- We must take a holistic view
  - Wells to wheels, cradle to grave
- We must address paradigm shifts
  - Organization and structure of urban and rural living, commuting, working, recreation, etc.
- Energy intensity of our life styles will become a controlling metric

Regardless of the Evolving Paradigm

- Power generation will still be a necessary aspect of our existence
- Our power generation systems will be constrained by:
  - Energy "use"
  - Emission impact

} Ecological Footprint

Reducing Carbon Emissions from our Power Generation Systems?

- Using power generation systems with non carbon energy carriers
  - Electric (batteries)
  - Hydrogen
    - Of course one must consider carbon emissions from energy source to the vehicle
- Recycle or sequester the carbon
  - Carbon sequestration
  - Bio-fuels
- Reduced fuel consumption for IC engines
  - Must also meet regulated emission standards

Alternate Fuels and Powerplants

- Electric Vehicles
  – Batteries
- Fuel Cells
  – Source of Hydrogen
  – Hydrogen Storage
- Bio-fuels
  – Still uses IC engine, the fuel is an oxygenated HC (has less energy)

Electric Propulsion

Battery Technology

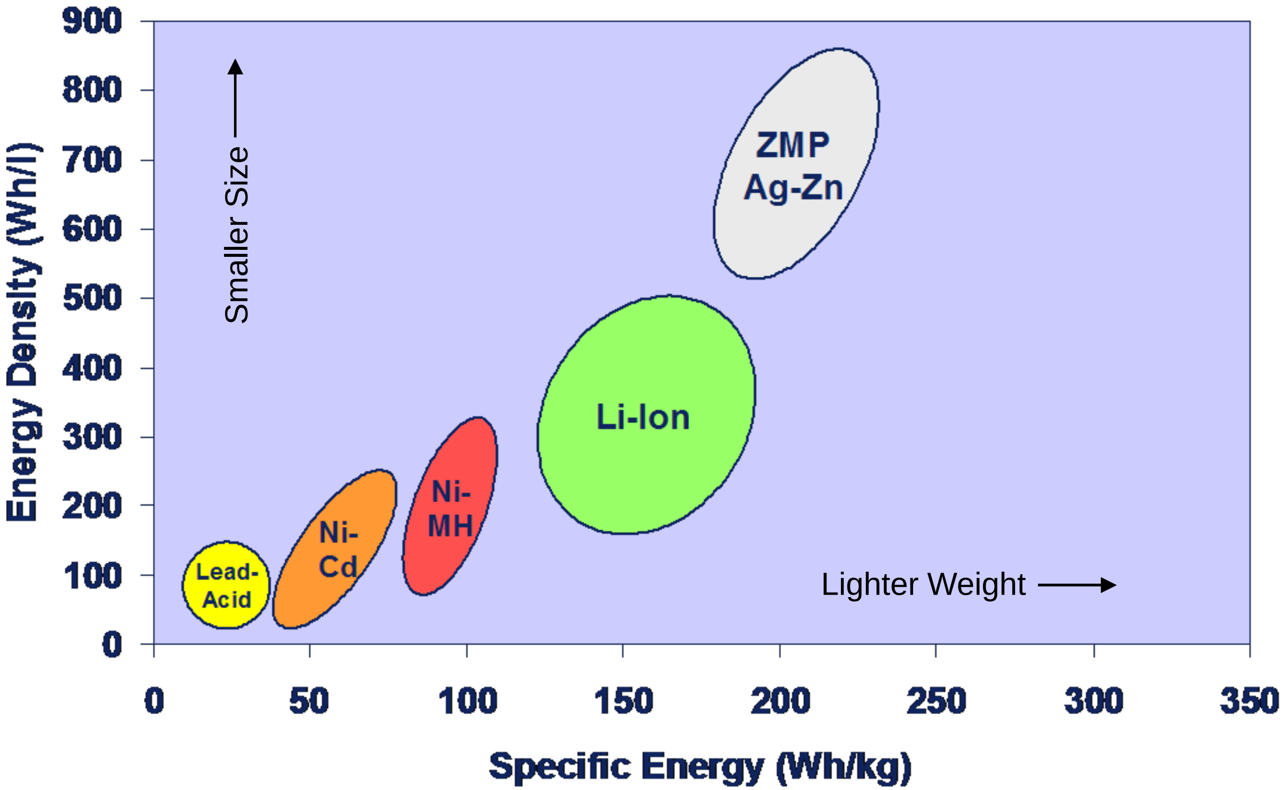
Battery Technology – Two Centuries Of Progress

1801 Volta Zn-Cu

1839 Fuel Cell
1859 Pb Battery
1899 Ni-Cd
1973 Li-Metal
1975 Ni-MH
1979 Li-Polymer

1990 Sony Li-Ion

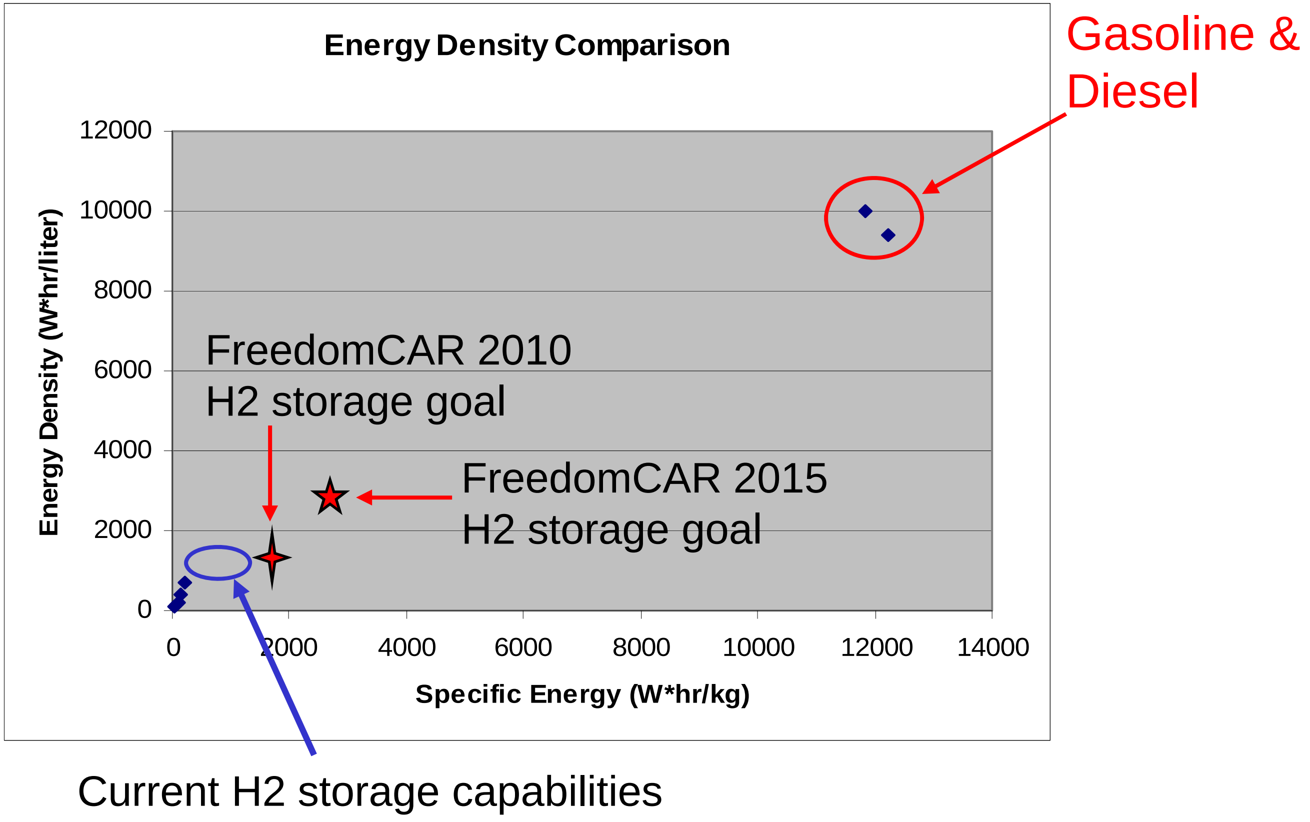
2000 Bellcore Plastic Li-Ion



Battery development generally proceeds from small sizes to larger sizes as the technology matures.

Source: Tarascon

Energy Content (continued)



H_2 information source: 1st NRC FreedomCAR Fuel Partnership Report, 2005

Comments

- Batteries offer the potential to electrons as an energy carrier from a portfolio of alternative energy sources
- Energy density of batteries will be significantly less than HC energy carriers
  - "The maximum theoretical potential of advanced lithium-ion batteries that haven't yet been demonstrated to work is still only about 6 percent of crude oil.“ - *The Limits of Energy Storage Technology, Kurt Zenz House, The Bulletin of Atomic Scientist, 20 January, 2009*
- Fuel cells will have to compete with battery electric vehicles
- There will be applications where it will be very difficult to displace combustion engines with HC fuels

Internal Combustion Engines

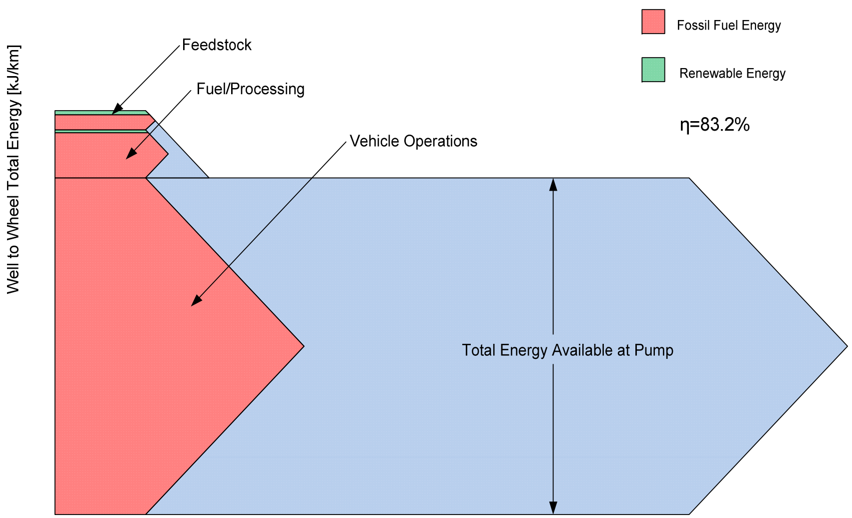
with

HC, or HCO Fuels

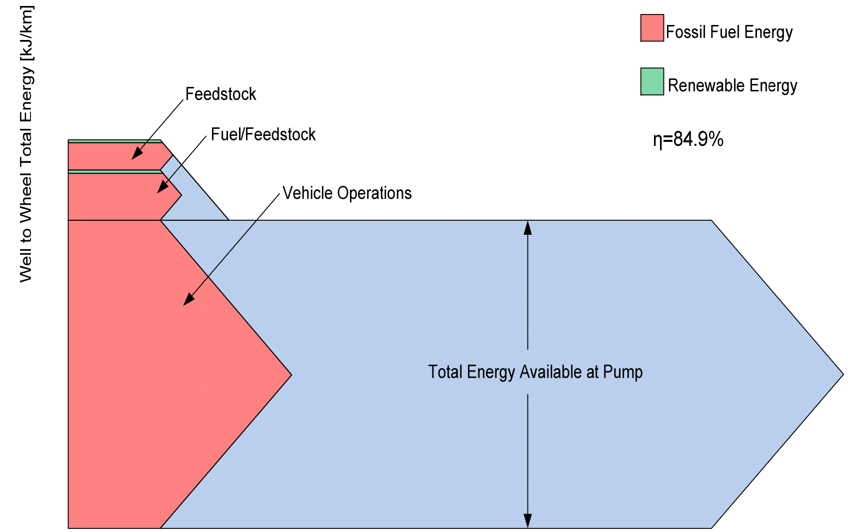
Bio-fuels?

- **Bio fuels are oxygenated HC's**
  - **They will not be as high in specific energy or energy density as gasoline or diesel. But they will be better than H_2 or batteries**
- **With Bio fuels you are "recycling" the carbon emissions**
- **Bio fuels are a complicated topic**
  - **Need to do accurate accounting of all growing, harvesting and processing energy and emissions**
    - **Water consumption, etc…**
  - **It appears that Bio fuels can be a contributor to the fuel pool, but are not THE solution**
  - **In terms of contribution, cellulosic bio-fuel is needed**

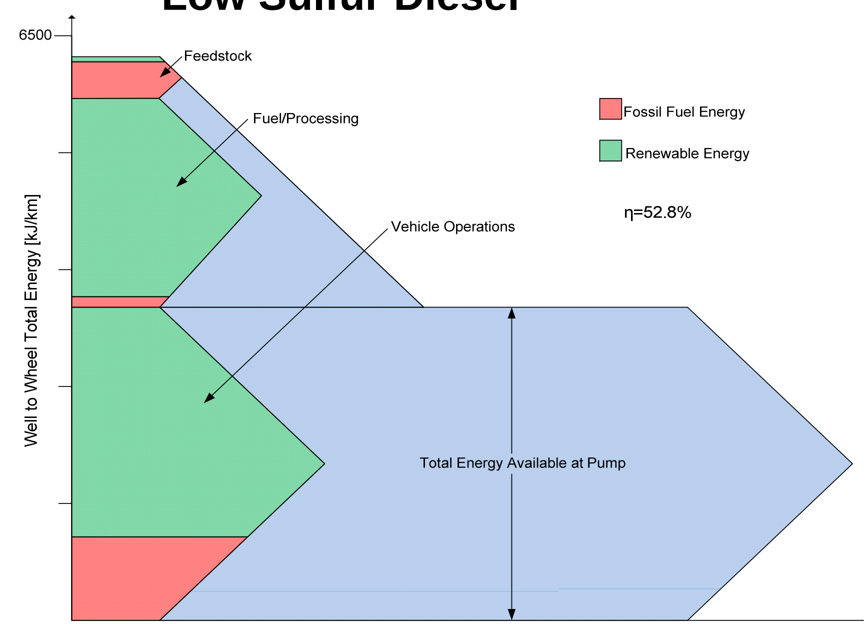
Well–to–Wheels Energy Footprint



Conventional Gasoline



Low Sulfur Diesel



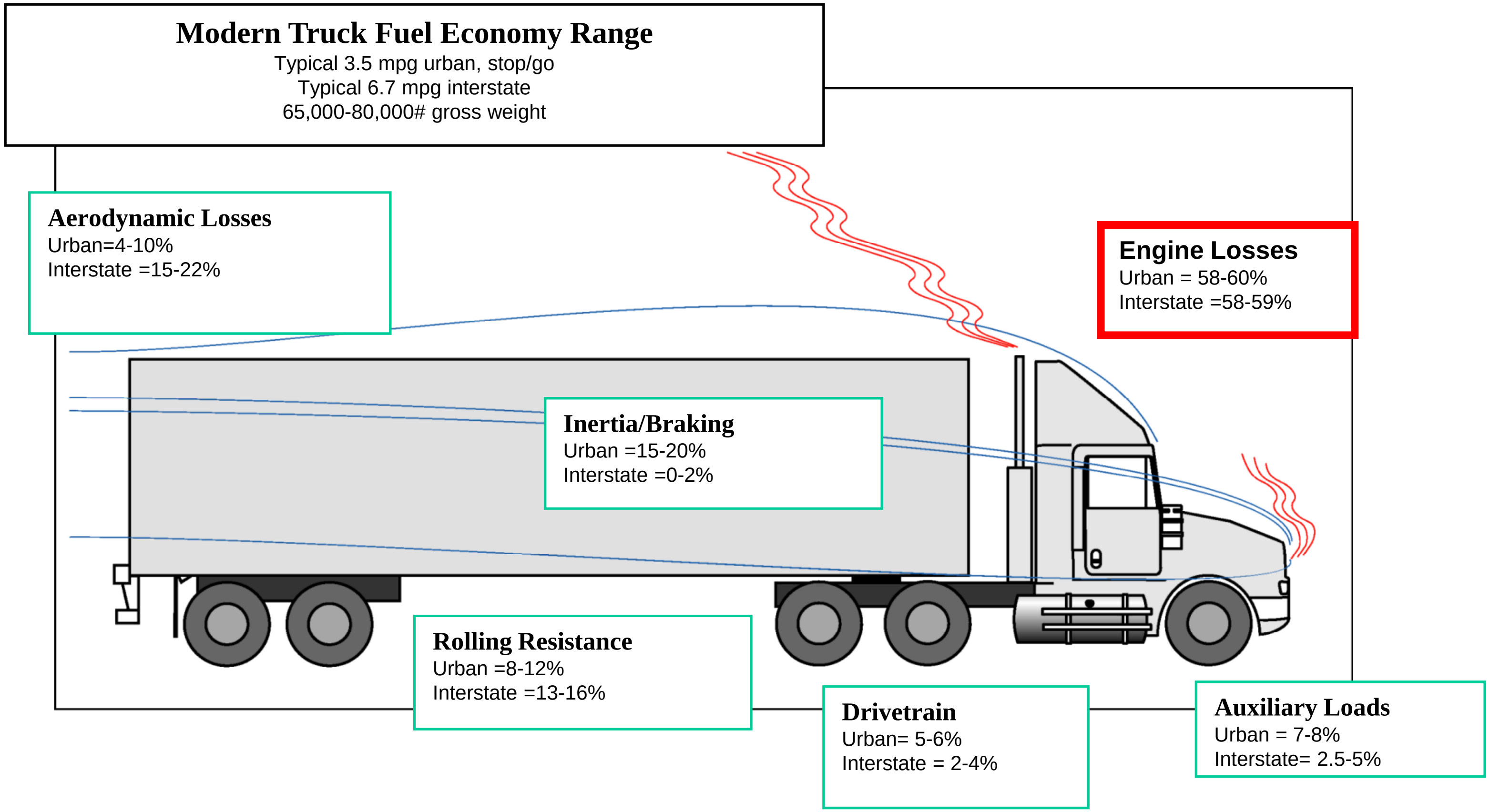
E85 Herbaceous Biomass**

Andrew Kaufman, UW Undergraduate, Independent Study using ANL GREET

****Herbaceous Biomass consists of organic plant material such as corn stover, wheat straw and switch grass**

Let’s Talk About Engines/Power Systems

System view of an Application's Energy Flow



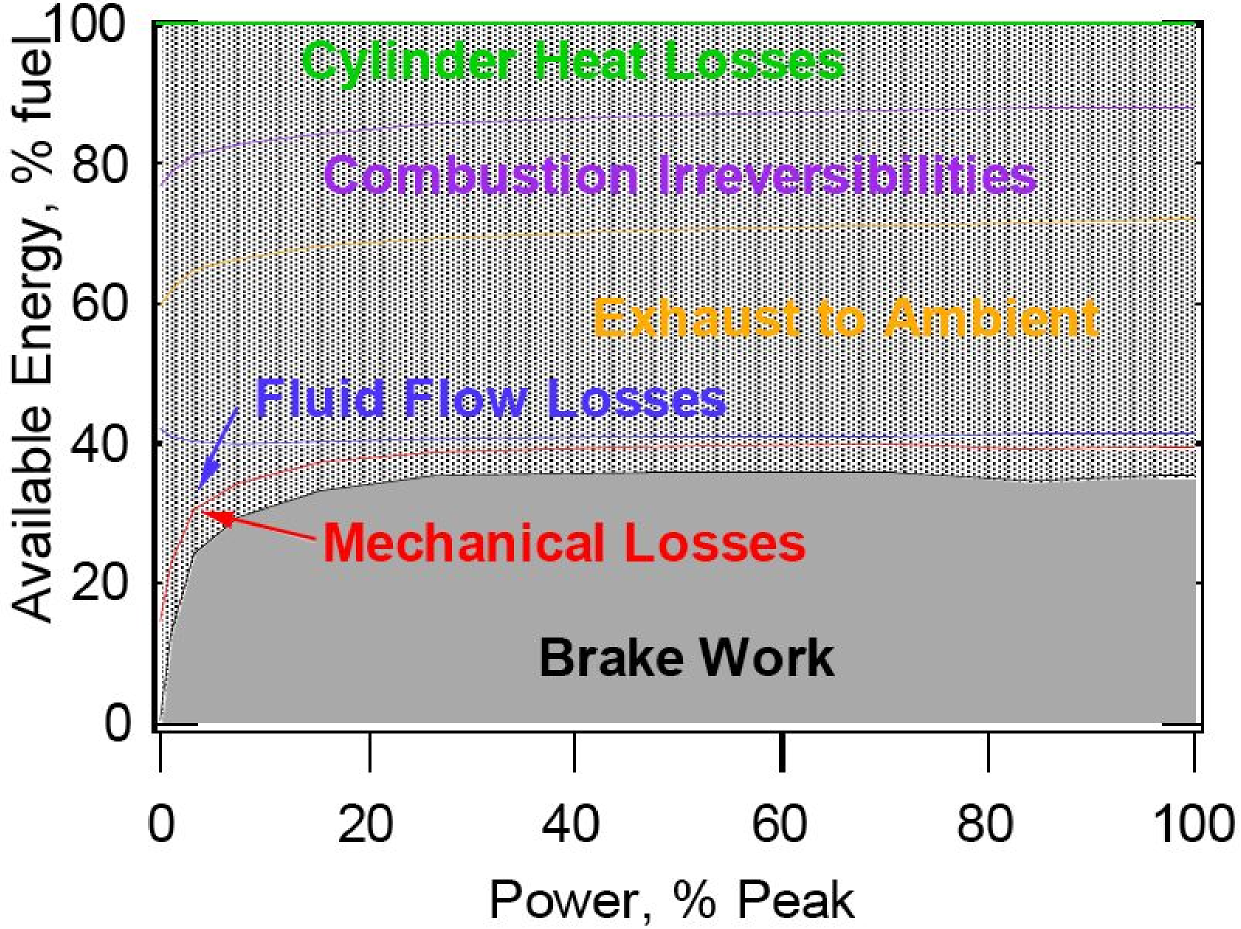
Class 8 truck energy audit from 21 CTP Roadmap, 2000
Updated Oct 2008

Every Application Has a Commensurate Diagram

- Hybridization may offer opportunities to load level or maintain engine "sweet spot" operation
  - Parallel and/or series hybrids
  - Electric or Hydraulic
    - Electric – applications where energy storage for longer times is beneficial
    - Hydraulic – applications where large power flows, with relative short storage times are required
- Optimization of a hybridized systems is dependent on the duty cycle
  - For many companies the duty cycle is viewed as proprietary information

Partitioning of the Fuel Energy

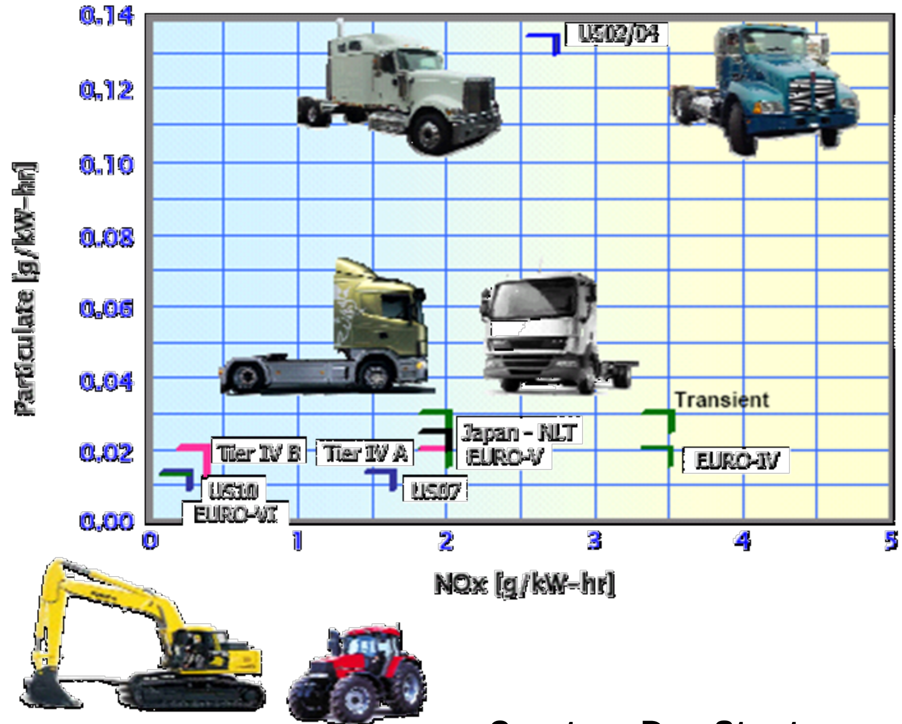
- **HC energy carriers are precious**
  - **Theoretical efficiency is 100%**
- **Availability partitioning diagrams show were the losses are**
- **Combustion irreversibilities are very hard to reduce**
  - **Would require a completely different engine**



Weissman, Walt, ExxonMobil, presented at UW-ERC, 9 June 2005

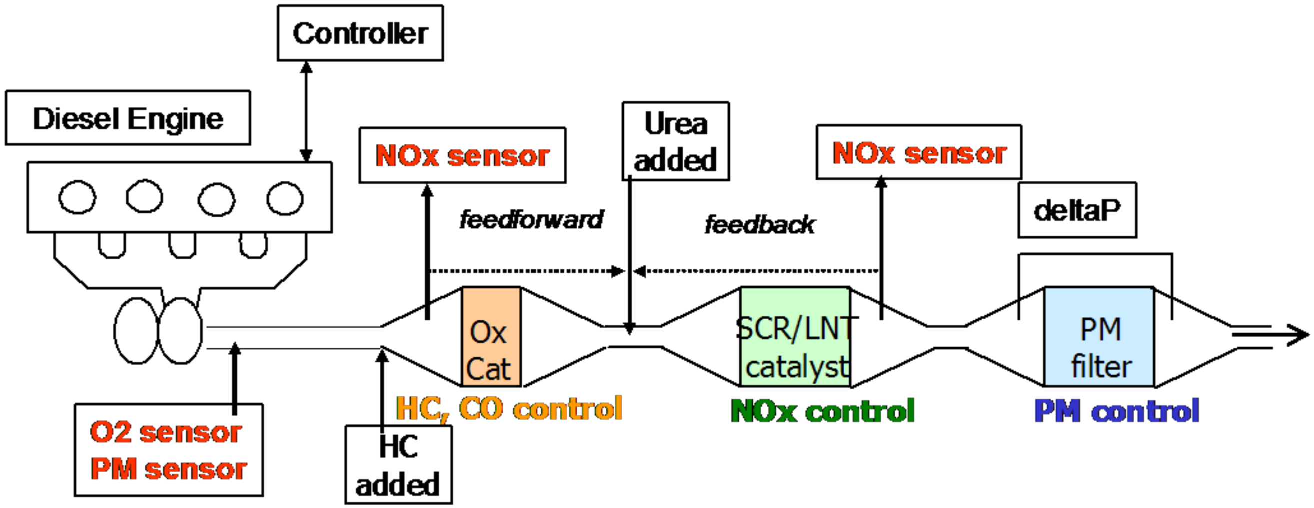
Engine Efficiency and/vs. Emissions

- Fuel economy will be "king"
- Emissions will still be a constraint
  - With increasing world population it is likely that emission regulations will continue to become more stringent
    - More applications will be regulated
    - New aspects of regulation will be introduced
      - Particulate number
      - More comprehensive tests
    - OBD will add new challenges



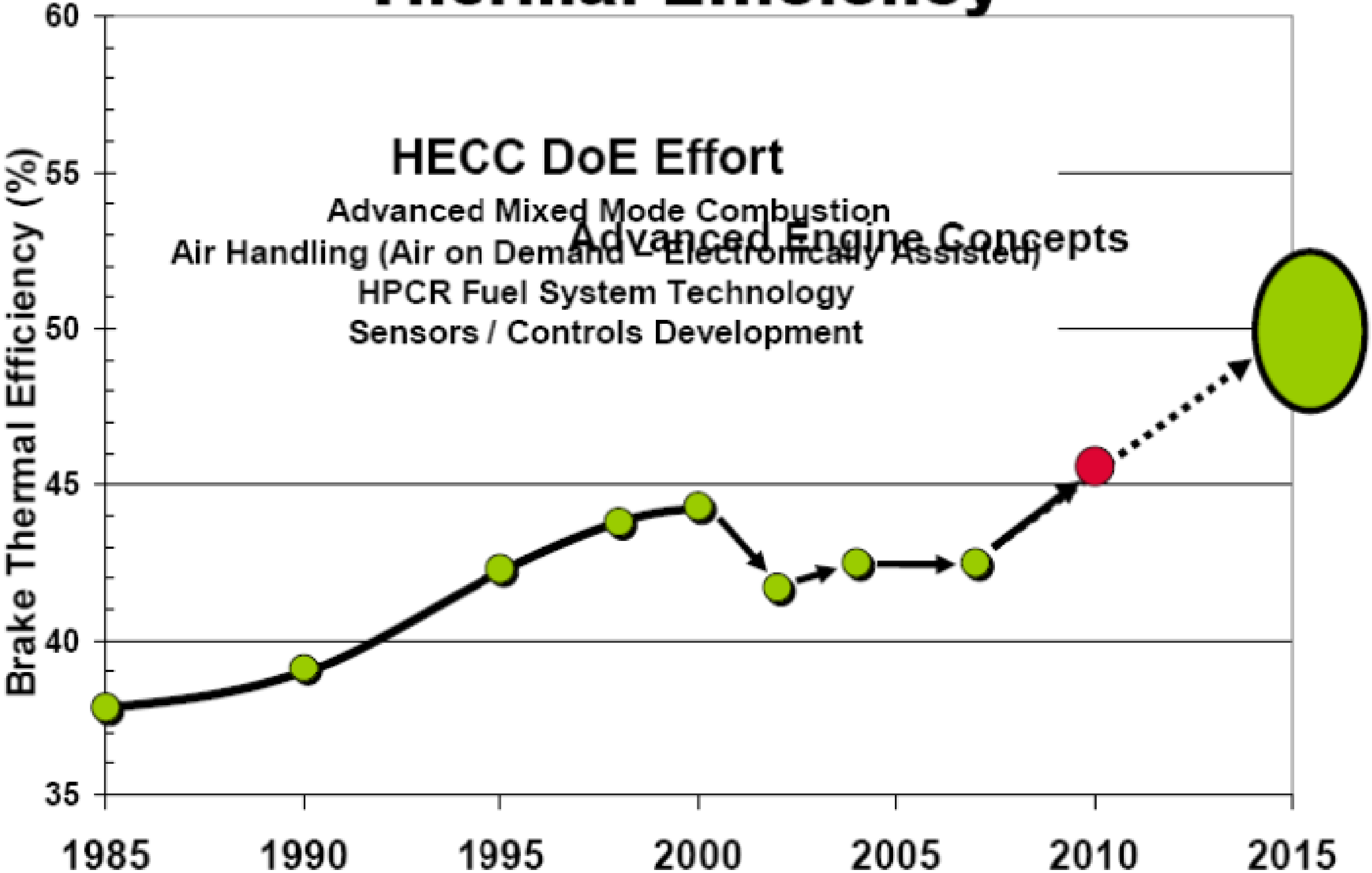
Courtesy Don Stanton – Cummins Inc

Powertrain Integration and Total System Optimization

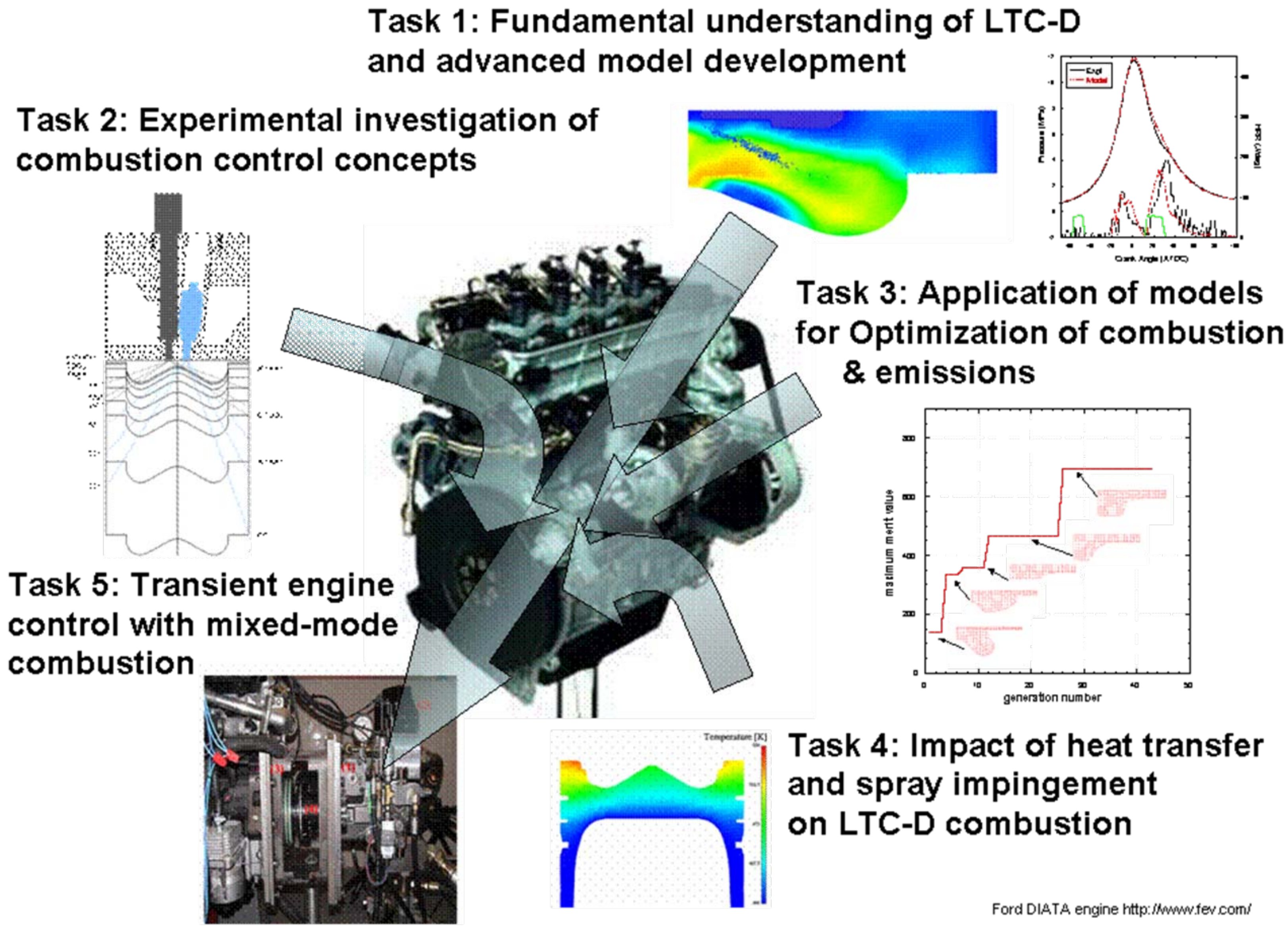


- The aftertreatment system, which is passive, will dictate the engine operating conditions
- Engine needs to supply the exhaust thermodynamic state and composition that is needed for optimum aftertreatment performance at that instant.
- Detailed fundamental understanding of each sub-system will be required

Historical Perspective of HD Brake Thermal Efficiency

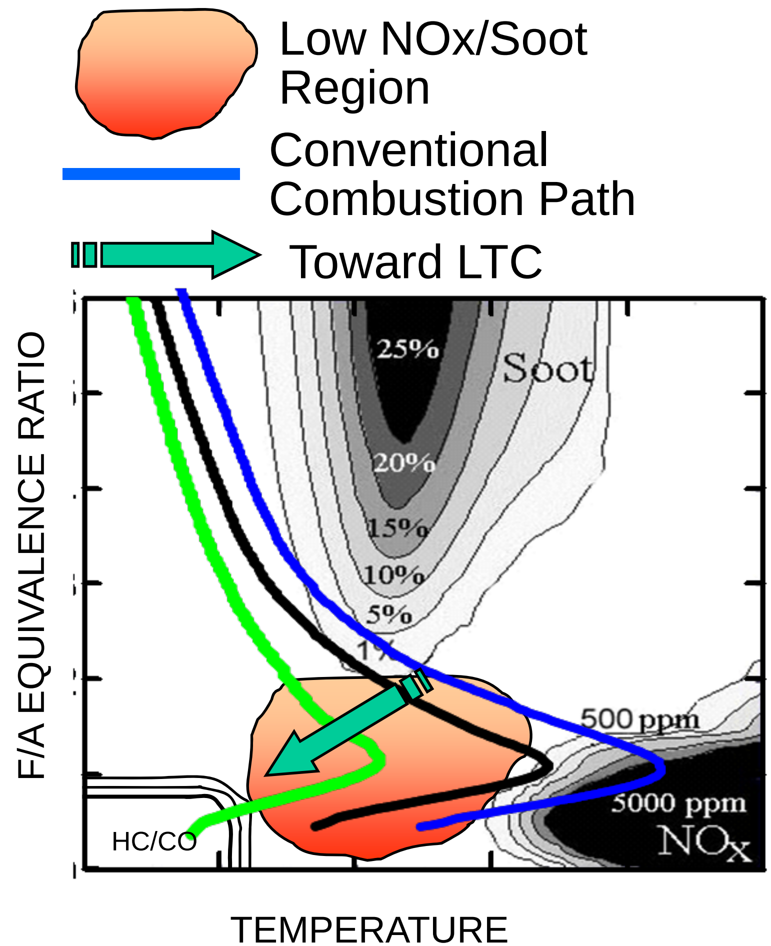


Combustion Optimization and New Combustion Regimes



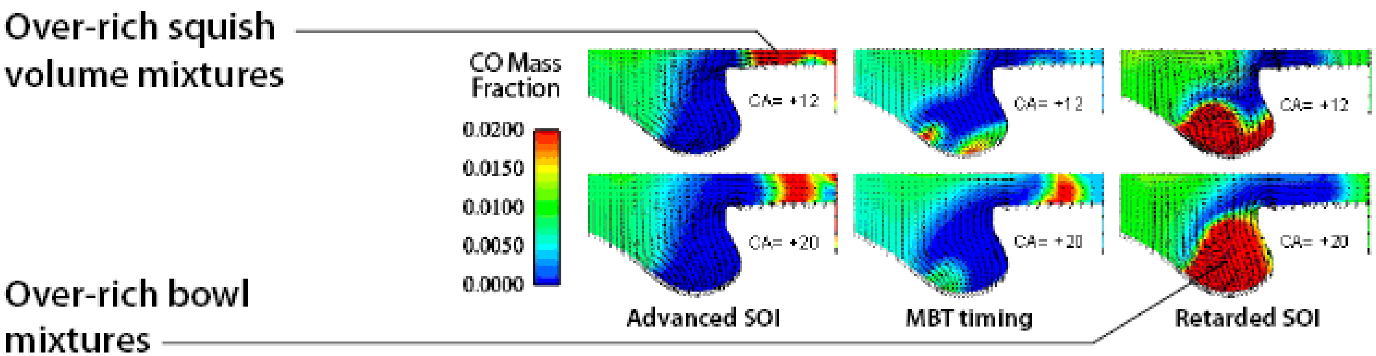
Low-Temperature Combustion (LTC)

- **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!**

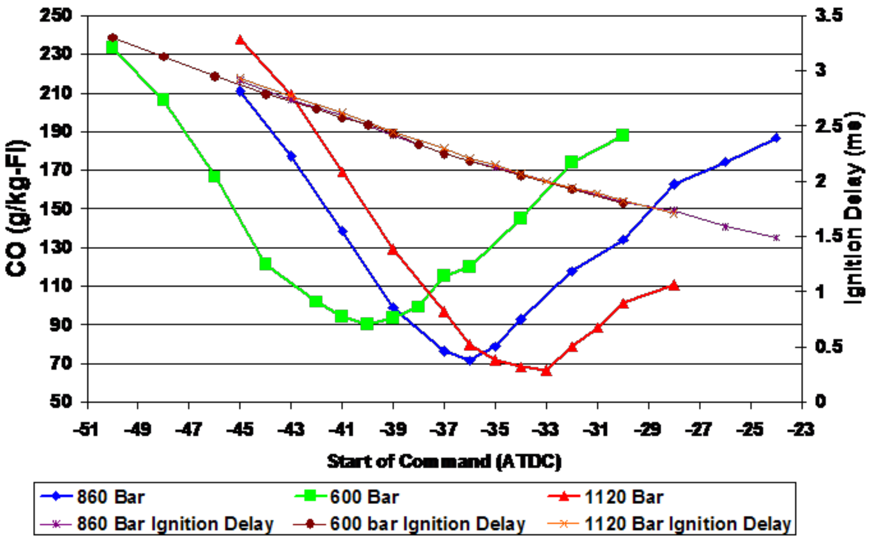


Concept was originally proposed by Kamimoto, SAE 880423

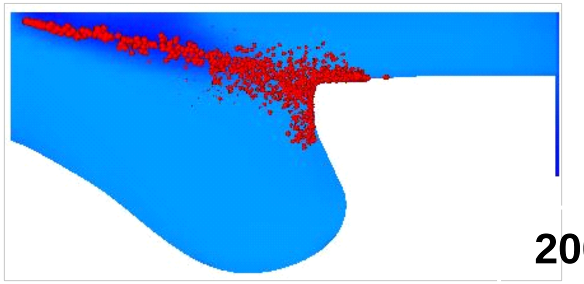
LTC Single Injection Research



From SAE 2007-01-0193 and SNL Research Overview



- **Carbon Monoxide Related Concepts**
  - Liquid fuel in squish region
  - Vaporized fuel at SOC
  - Bulk fluid mixing
  - Spray targeting
  - “Sweet Spot” injection targeting



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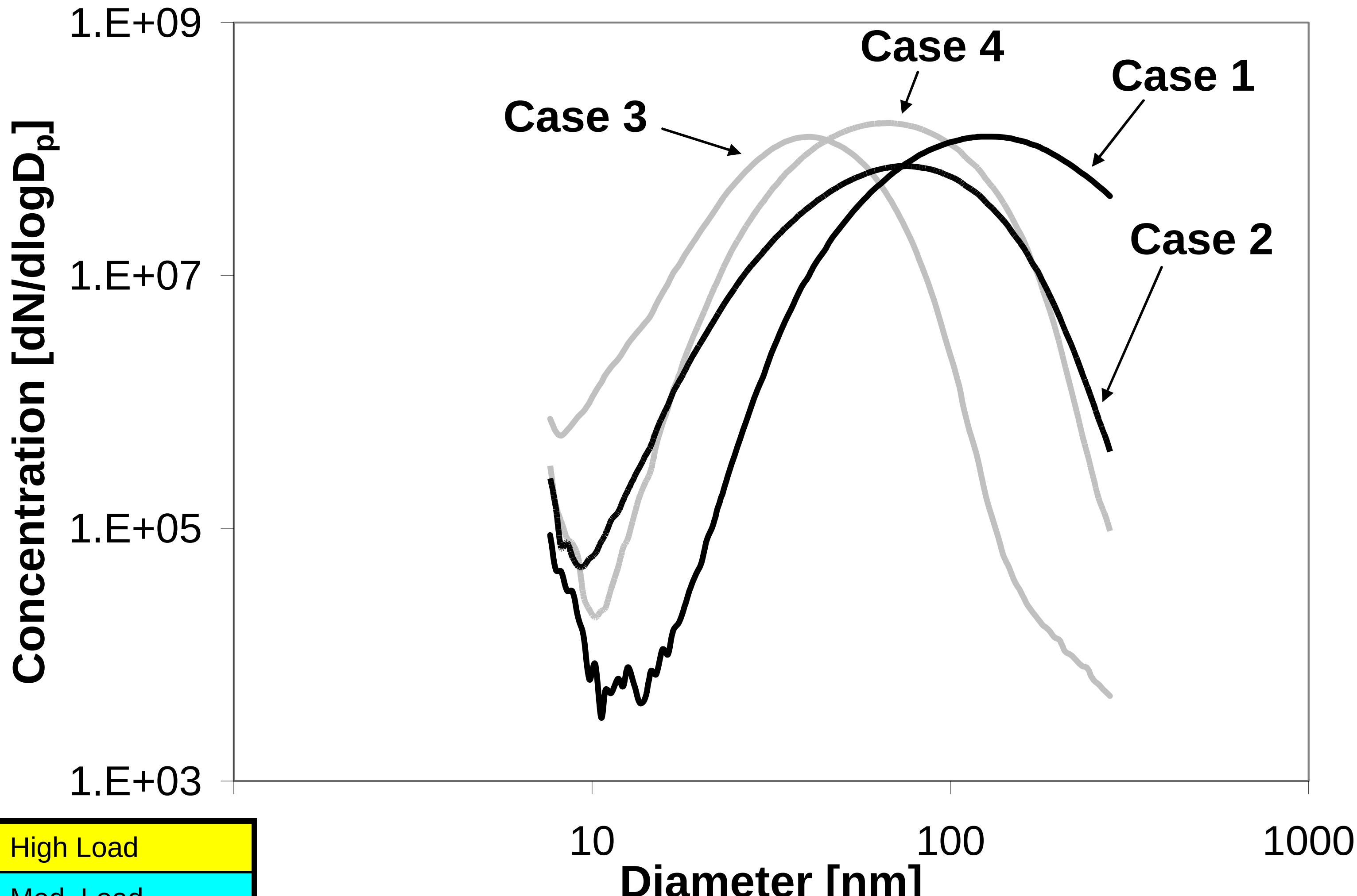
SMPS Size Distribution



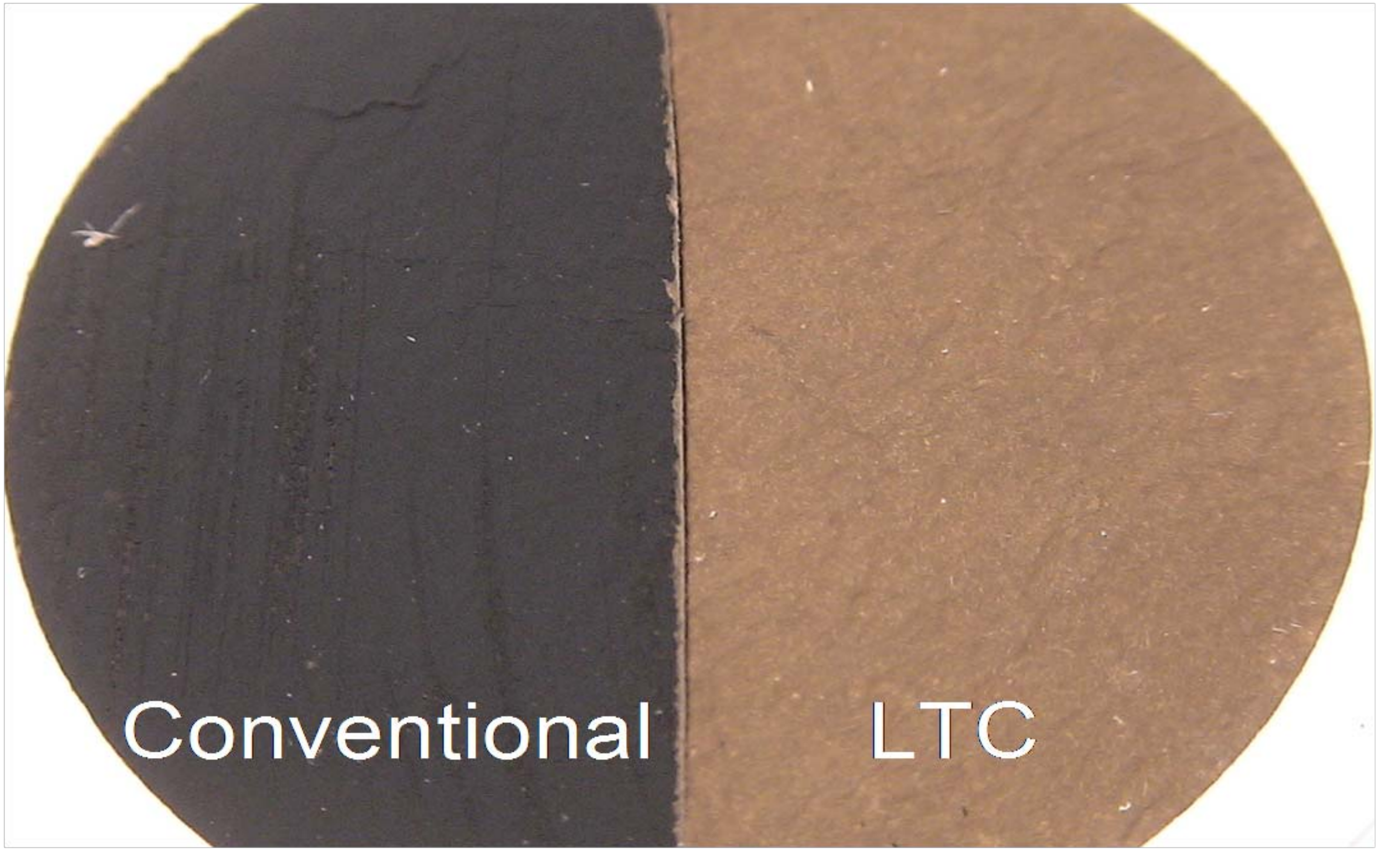
1	Conv. High Load
2	Conv. Med. Load
3	LTC High Inj. Pressure
4	LTC Low Inj. Pressure

Size and Mass Statistics

Case	1	2	3	4
Total Number Concentration [#/cc] xE9	4.05	2.42	3.12	5.08
Geometric Mean Particle Diameter [nm]	120	70.3	38.8	64.6
Mode [nm]	126	76	40	69
Teflon Filter Mass [g/kg_fuel]	2.4	0.39	0.08	0.47

1	Conv. High Load
2	Conv. Med. Load
3	LTC High Inj. Pressure
4	LTC Low Inj. Pressure

Filter Analysis



Color difference between PM from Conventional and LTC diesel combustion

Unconventional Fuels in Unconventional Engines?

- “Gasoline, The Best Fuel for Diesel Engines” ERC Symposium 2007, Kalghatgi et al. (SAE 2007-01-0006)
- Operating a Heavy-Duty Direct-Injection Compression-Ignition Engine with Gasoline for Low Emisisons (SAE 2009-01-1442)

Operating a Heavy-Duty Direct-Injection Compression-Ignition Engine with Gasoline for Low Emissions

- 2009-01-1442

- Authors - Reed Hanson, Derek Splitter and Rolf Reitz

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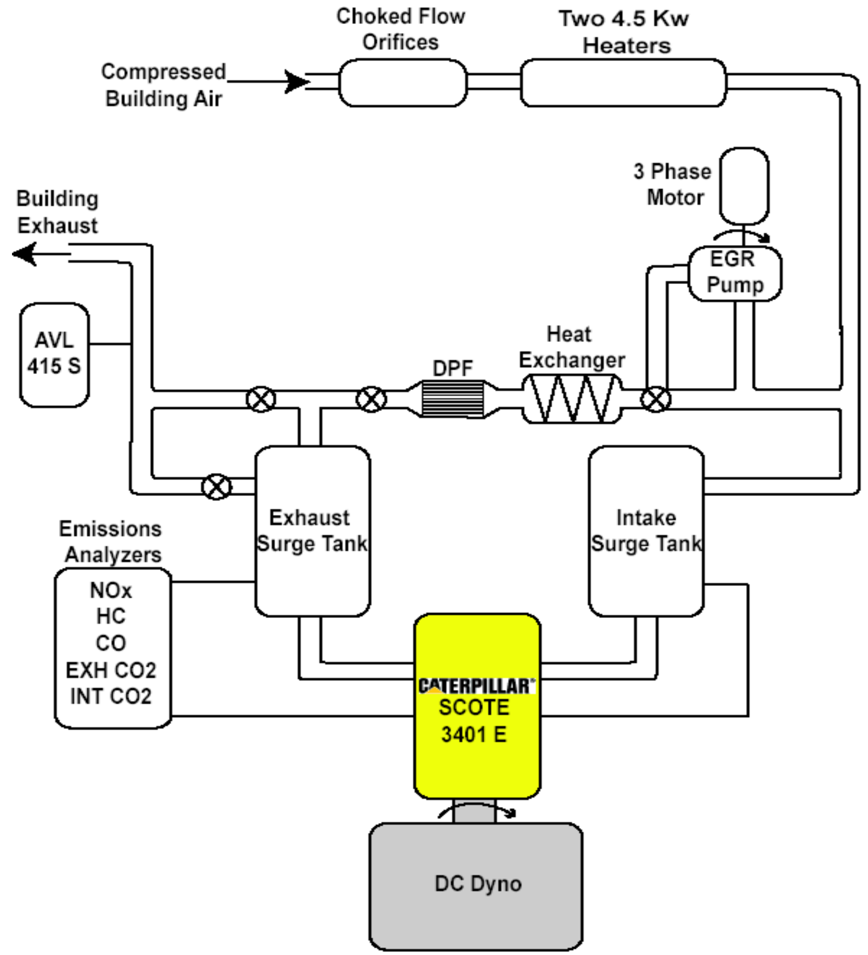
Department of Energy/Sandia National Laboratory

- Contract DEFC26-06NT42628

SETUP ENGINE LAB

3401E SCOTE Geometry

Displacement (l)	2.44
Geometric Compression Ratio	16.1:1
Bore (mm)	137.20
Stroke (mm)	165.10
Connecting Rod Length (mm)	261.60
Squish Height (mm)	1.57
Number of Valves	4
IVC (deg BTDC) (modified cam)	85.00
IVO (deg ATDC)	335.00
Swirl Ratio (stock)	0.7
Piston Type	Articulated
Piston Bowl Geometry	Stock
Effective Compression Ratio	9.1:1



SAE 2009-01-1442

SETUP EXPERIMENTAL CONDITIONS

EGR

- Gasoline PPC Experiments

- Double injections
- A50
  - Pilot SOI
  - Pilot / Main Split %
  - Intake Pressure
  - Main SOI
  - EGR
  - Low Load (A25)

- Single Injections
- A50 with 40% EGR

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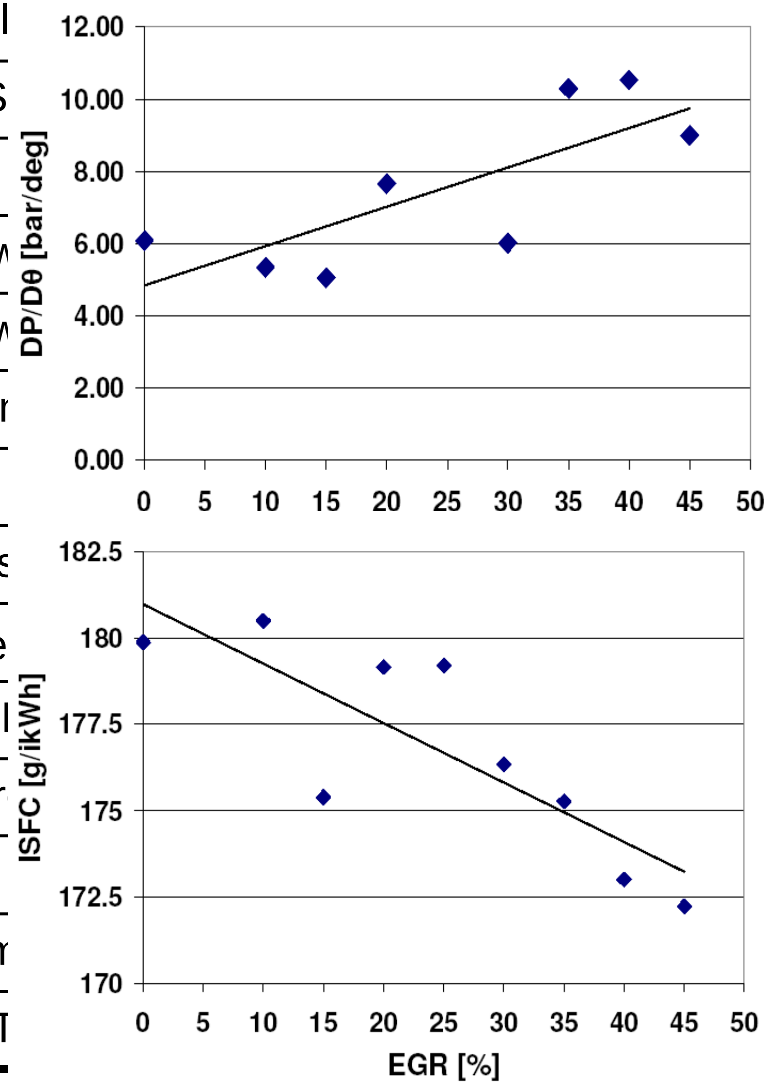
Base Operating Conditions

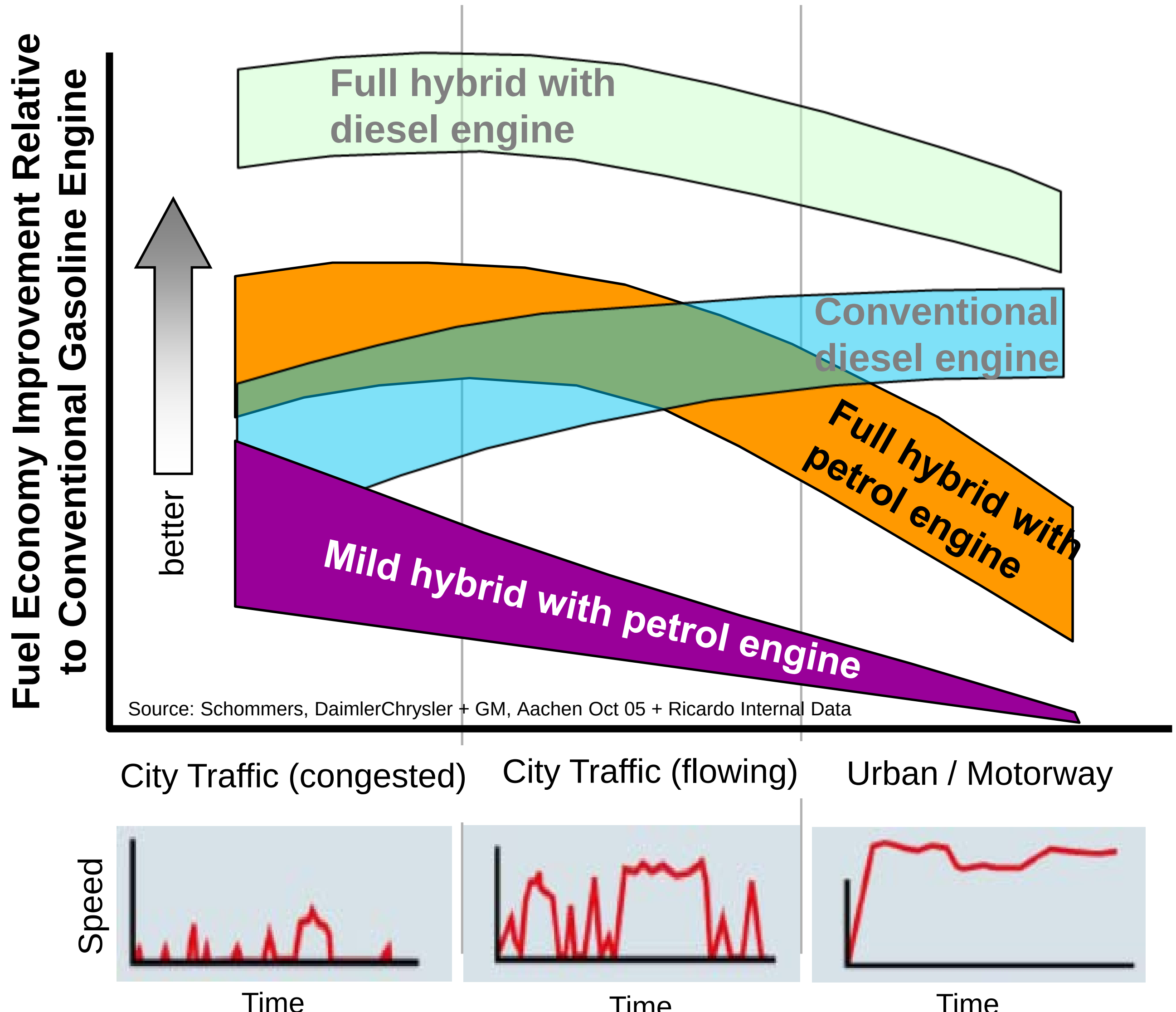
FTP Cycl
Engine S
IMEPnet
Fuel Flow
Fuel Flow
Pilot/Mai
Pilot SOI
Fuel Pres
Intake Te
Exhaust I
Intake Pr
EGR [%]
Maximum
CA50 [AT



Closing Comments

- Energy Intensity of our life styles will be an important metric
- Power generation in IC engines from HC, or HCO fuels will not go away
  - Total system optimization will offer significant reduction in fuel consumption
- Significant improvements in IC engine performance are still possible
  - Advanced and novel combustion regimes offer promise if they can be incorporated into the operational map
  - Enhanced fundamental understanding incorporated into computer simulations will be required to achieve these benefits
- Meeting emission standards and maintaining compliance will be an increasingly challenging constraint
- This is a time of tremendous opportunity, and unfortunately tremendous stress

Hybrid Systems - higher fuel economy in congested traffic - diesel more efficient than hybrid gasoline in higher speed free flowing traffic – diesel hybrid best but expensive



- **Relative merits of Diesel or Hybrid depend on application and drive pattern**
- **Stop/start and low speed driving favours Hybrid configuration**
- **Higher speed operation requires high efficiency combustion and driveline**
  - **"Electric Transmission" always less efficient than mechanical system**

Slide from Neville Jackson - Ricardo

Recently I Filled Our Car With Gas

- **Eleven (11) gallons in 90 seconds**
  - – **This in an amazing power transfer**
    - **15.2 MW**
    - **20,440 HP**
    - **33 people filling their cars at the same time is equivalent to a 500 MW powerplant**
- **To transition to other energy carriers and/or powerplants we will need to change our paradigm on mobility**

What about Total CO_2 Emissions?

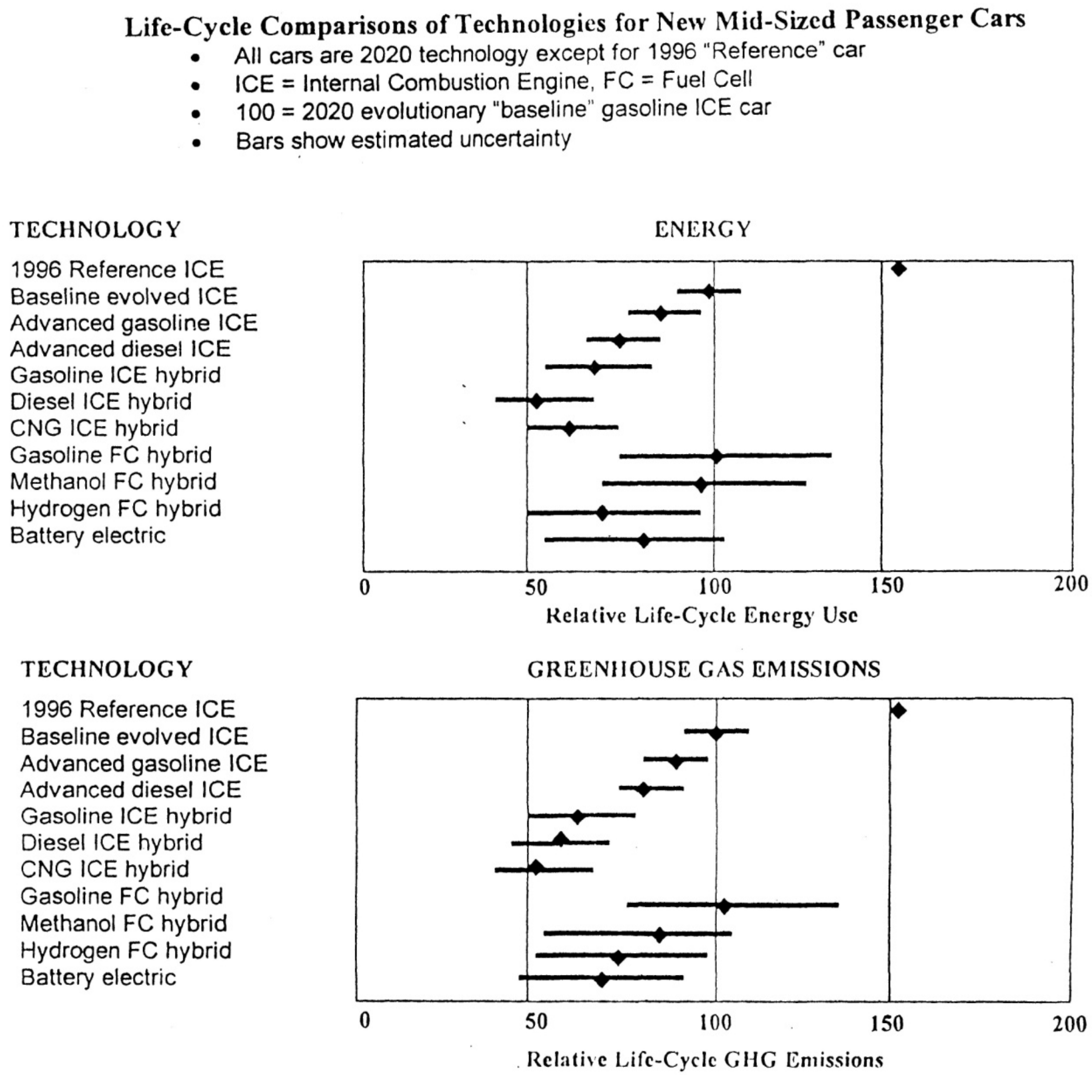
Life Cycle Energy Costs

&

Wells to Wheels?

Total Energy and Carbon Emissions for Different Powerplants*

- **Significant improvement over the current engines is likely**
- **Uncertainty is significant**
- **Diesel hybrid and CNG ICE hybrid seem pretty good**



*** On the Road in 2020, A life-cycle analysis of new automobile technologies Energy Laboratory Report # MIT EL 00-003**

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

Practical Aspects of Transitioning New Technologies into the Market (continued)

- **Electric vehicles?**
  - At current rate of progress, battery energy density will be doubled in 10 years (2016)
    - Perhaps this could make an electric commuter vehicle plausible
    - Construction of manufacturing facilities to introduce electric commuter vehicles as a significant portion of the vehicle population (10 years?)
    - Time for the vehicles to penetrate the market to significant percentage (20 years + ?)
  - Several decades will be required for significant impact from electric vehicles

Assessment

- Even under the most optimistic scenarios, it will be many decades for radically different powerplant and energy carrier technologies to penetrate the vehicle market to proportions that will be significant relative to current system
  - Even still, these technologies will hold a minority portion of the market
- Current powerplants will continue to be a dominant player in the mobility market for many decades to come
- Improvements in current powerplant and fuel technologies will have an impact that is cumulative and be integrated over the decades that it takes to introduce new systems, should they be developed.

Assessment (continued)

- The internal combustion engine fueled with HC, and/or HCO fuels, will be a viable competitor to alternative propulsions system for decades to come. (Hybrids are included in this statement)
  - It will be competitive in terms of:
    - Life cycle energy cost
    - Total environmental impact
    - Financial cost to the consumer
  - It will probably maintain superiority to the competition in terms of:
    - Range between refueling
    - Power density
- Improvements made to the IC Engine today will have an integrated impact starting immediately

What is Needed?

- **We must get serious about reducing fuel consumption**
  - **Fuel consumption of a vehicles scales directly with its:**
    - **Mass, frontal area and power-to-weight ratio**
      - **The efficiency of IC engines has been improving steadily for the last several decades, however the US market has used those efficiency gains for increased performance, not reduced fuel consumption**
  - **Enhanced safety features typically add mass to vehicles – which increases fuel consumption**
- **We need to change our paradigm regarding mobility.**

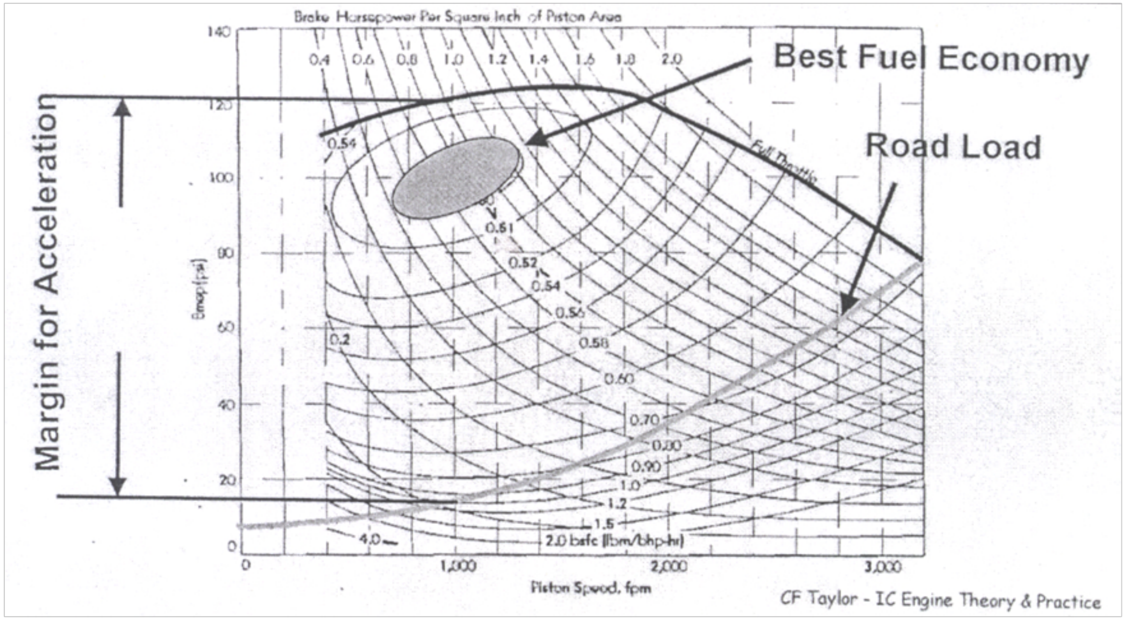
Where will the improvements in IC engine powertrains come from?

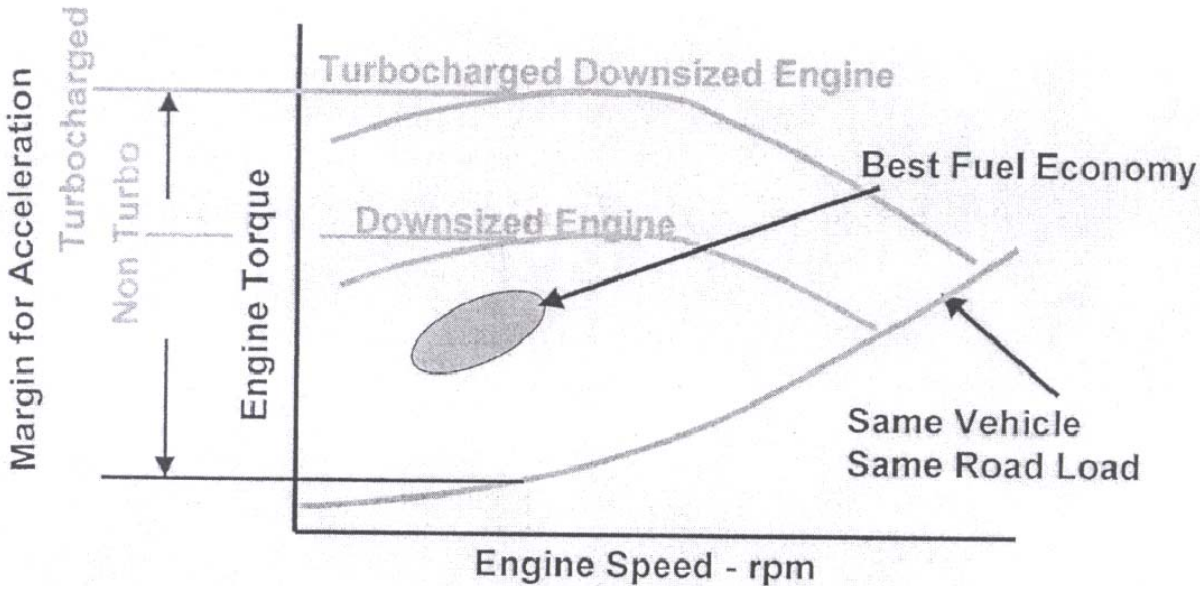
Summary

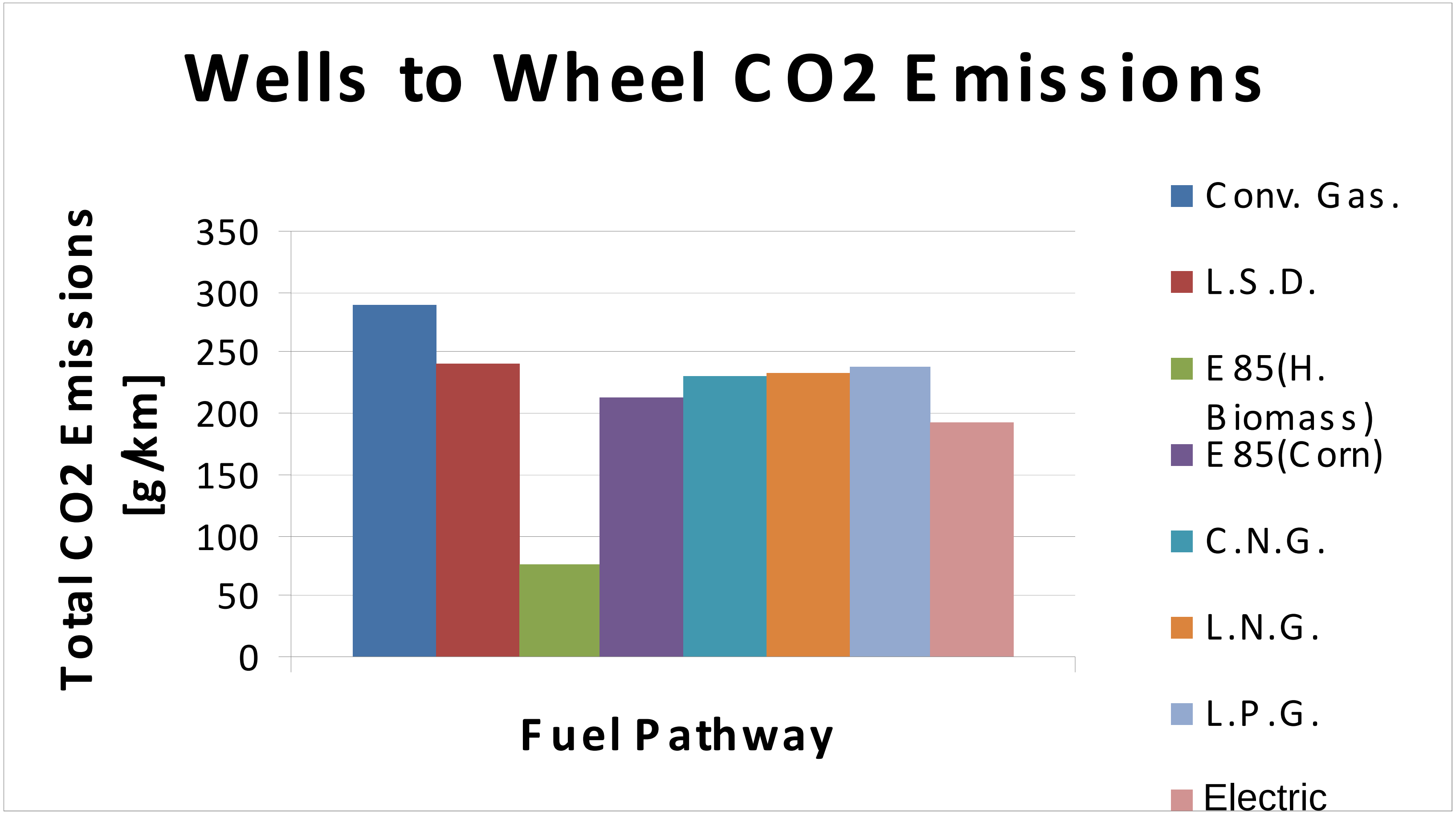
- HC, or HCO, fuels will continue to be the energy carrier for mobility systems for decades to come.
- IC Engines, including hybrids, will be viable powerplant for decades to come
- To simultaneously minimize carbon emissions and regulated "pollutants" each individual component of the system will need to be thoroughly, and fundamentally understood, and optimized in a system configuration.
- This thorough and fundamental understanding is lacking in many of the system components being considered for 2010 and beyond.
- Experimental investigations, coupled with detailed and system modeling will be critical aspects of the path forward.

Downsizing and Turbocharging, SI

- Engine runs less throttled
  - less pumping work
- With direct injection SI knock margin increases
- Intercooling is needed to keep temperatures down
- High pressure multiple injection capability needed to optimize performance over all operating conditions
- Λ=1 operation allows for proven aftertreatment systems to be applied







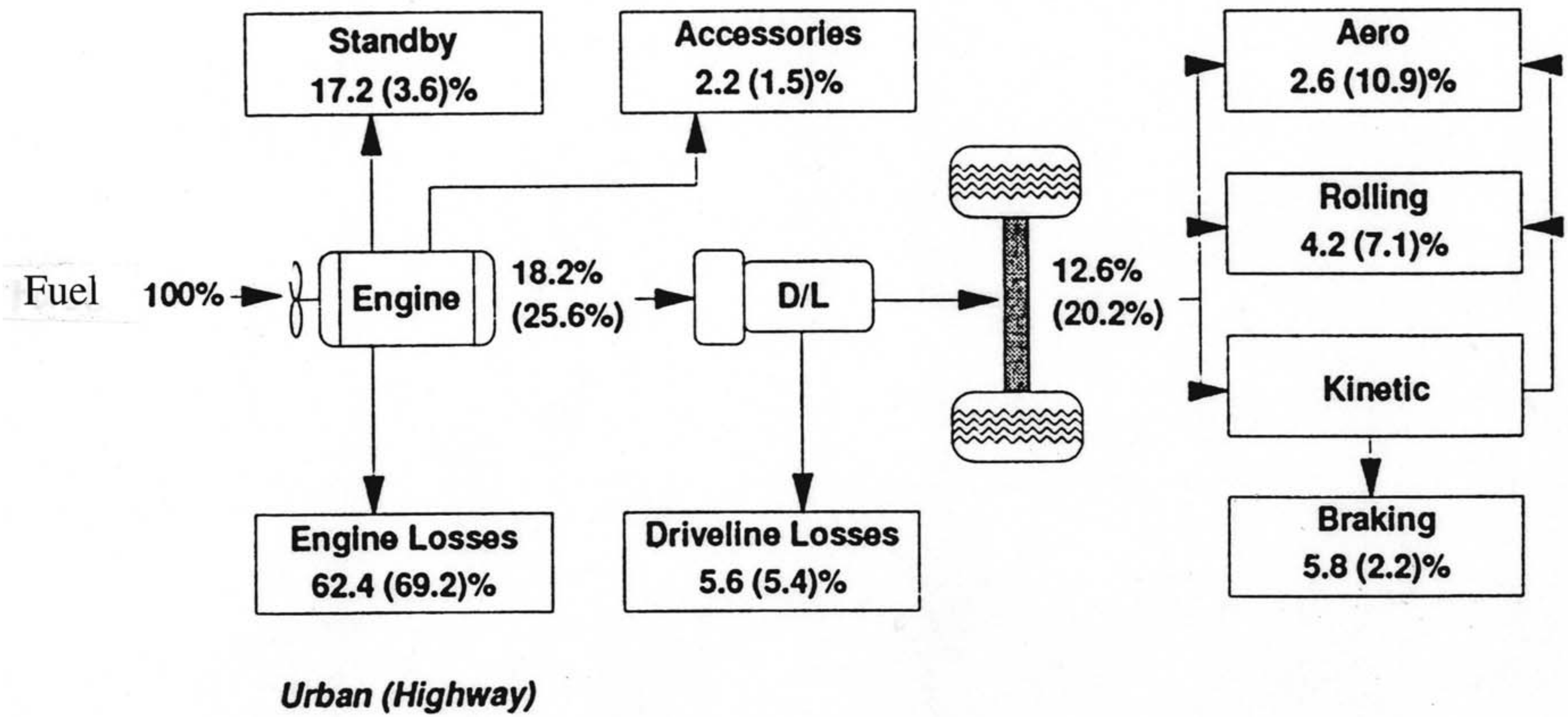
Andrew Kaufman, UW Undergraduate, Independent Study using ANL GREET

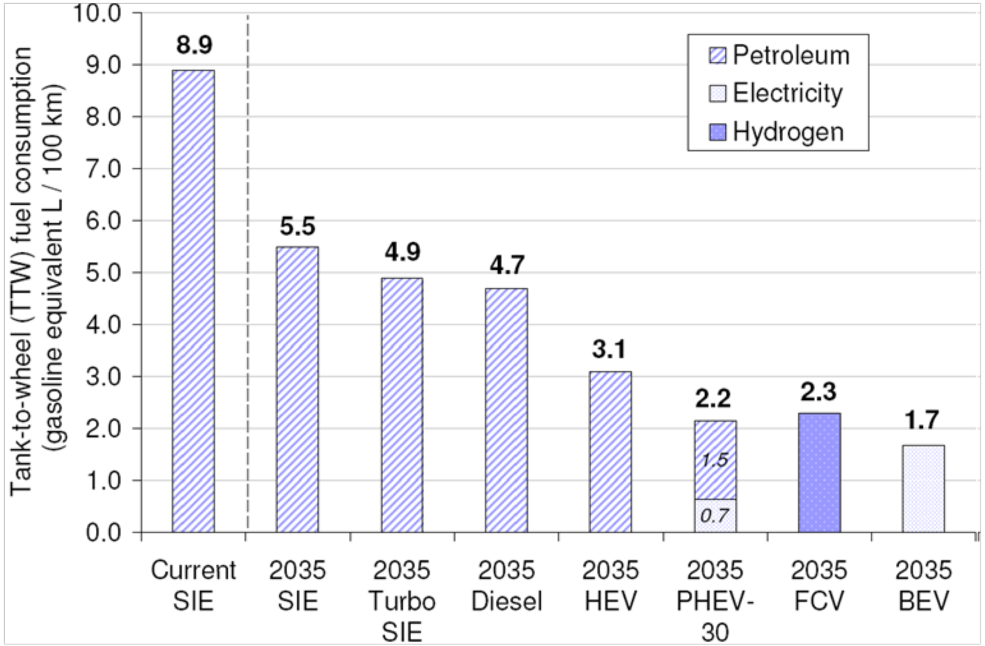
Reducing CO_2 via Fuel Choice*

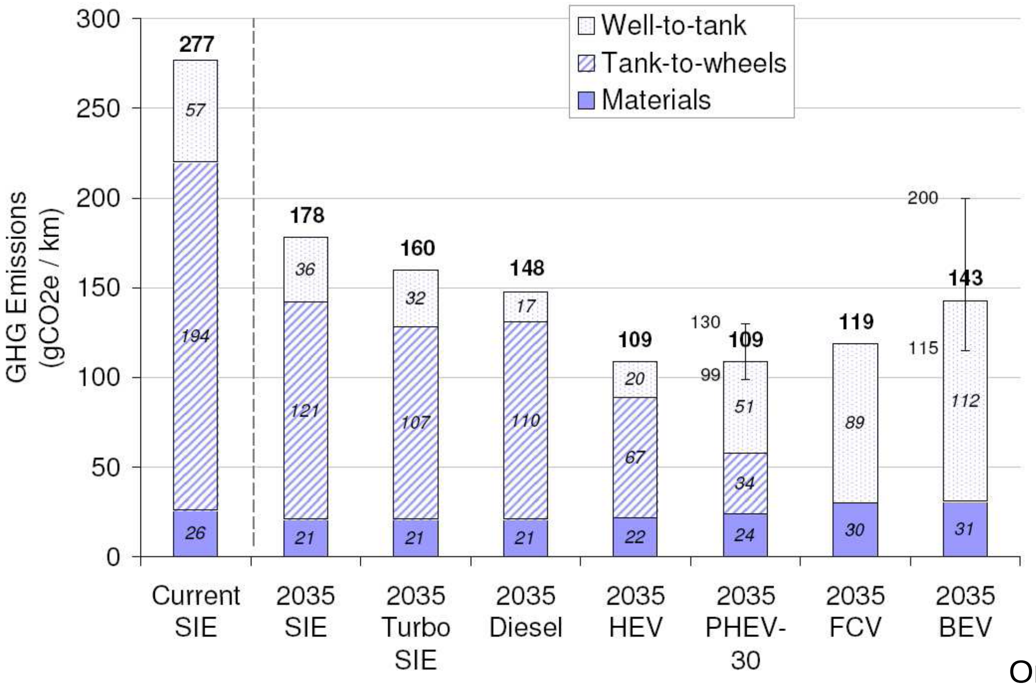
- Currently, the Canadian oil-sands reserves are supplying about 3% of total U.S. fuel use.
- This could expand to about 10% of total U.S. consumption in 2030, resulting in a 5% increase in well-to-tank GHG emissions.
- Ethanol might displace about 10% of gasoline by 2025 but increased use of non-conventional oil is likely to largely offset this effect

* On The road in 2035
http://web.mit.edu/sloan-auto-lab/research/beforeh2/otr2035/

Energy Distribution in a Mid-Size Car (PNGV)







Predicted Fuel Consumption and Greenhouse Gas Emissions for Different Powerplants

- **HEV and PHEV offer best potential for minimizing CO_2 in the near and mid term time frames**
  - **CO_2 emission from PHEV will depend on the electricity generating mix**
- **Not shown are costs of the technologies**
  - **Turbo SI and Diesel are most cost competitive**

On The road in 2035
http://web.mit.edu/sloan-auto-lab/research/beforeh2/otr2035/