On the Road to Clean and Efficient Powertrains

Prof. Dennis Assanis
Jon R. and Beverly S. Holt Professor of Engineering
Mechanical Engineering, University of Michigan
Energy, Carbon and Climate

- World energy consumption projected to increase 50% by 2030
- Current energy mix not sustainable
- Greenhouse Gas Emissions are projected to increase significantly
- Transportation:
  - 28% of energy use in U.S., 95% petroleum fueled
  - Average fuel conversion efficiency: 20%
  - Contributes 34% of U.S. CO₂ emissions

How do we meet future demand with clean and affordable energy sources?

EIA, IEO 2007

NASA Earth Observatory, based on IPCC Fourth Assessment Report
Technology Drivers

Fuel Resources

Emissions (CO$_2$, NO$_x$, Soot)

Source: Oak Ridge National Laboratory, Carbon Dioxide Information Analysis Center: http://cdiac.ornl.gov/
Energy Conversion Options for the Next Generation of Vehicles

Energy Storage:

*Batteries, hydraulic accumulators, flywheels*

Clean Combustion Technologies

Hybrid Propulsion Options

Fuel Cells

Alternative Fuels:

*Bio-fuels, Synthetic fuels, Hydrogen*

http://arc.engin.umich.edu
Main Theme in the Future: Energy and Powertrain Diversity

- Spark Ignition engine
- Compression Ignition engine
- Gas/Diesel
- Advanced SI engine
- Hybrid powertrain
- Advanced CI engine
- Fuel Cell
- $H_2$ engine
- Electric powertrain
- Alternative Fuels
Well-to-Wheel Efficiency

WELL

Refinery

Power Plant

IC Engine

Fuel Cell

Reformer

EV

WHEEL

10-6
What is the Preferred Powertrain of the Future?

Kreith et al., Transportation Quarterly (2002)


Well-to-Wheel Efficiency

Overall (well-to-wheel) efficiency of the TOYOTA FCHV

<table>
<thead>
<tr>
<th>Fuel efficiency</th>
<th>Vehicle efficiency</th>
<th>Overall efficiency (well-to-wheel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline vehicle</td>
<td>88</td>
<td>16</td>
</tr>
<tr>
<td>Prius (gasoline)</td>
<td>37</td>
<td>5%</td>
</tr>
<tr>
<td>FCV (compressed hydrogen)</td>
<td>58%</td>
<td>38%</td>
</tr>
<tr>
<td>TOYOTA FCHV</td>
<td>50%</td>
<td>22%</td>
</tr>
<tr>
<td>FCHV (target)</td>
<td>70%</td>
<td>60%</td>
</tr>
</tbody>
</table>

In the Japanese 10-15 test cycle, Toyota in-house testing +5 Efficiency if hydrogen is produced from natural gas and trucking fuel to filling stations for internal-combustion engines is more efficient than creating hydrogen for fuel cells.

Kreith et al., Transportation Quarterly (2002)


Sae 2003-01-0415

Powertrain Efficiency

Tank to Wheel Efficiency

Well to Wheel Efficiency

ICE: Internal Combustion Engine
HEV: Hybrid Electric Vehicle
CIDI: Compression-Ignition Direct-Injection
H2: Station Generated Hydrogen
FCV: Fuel Cell Vehicle

Source: US Department of Energy
Future of ICES

• Traditional Internal Combustion Engine will not Disappear Overnight
  – Economic and societal impact

• Hard to Beat
  – High power and energy density
  – Low specific cost
  – Robust and versatile
  – Well matched to available fuels
  – Met performance, fuel economy and emission requirements to date

Reproduced from Key, Distributed Power Program Quarterly Review (2001)
Gasoline Engine:
Very Clean But Not So Efficient

Port Fuel Injected

Stratified Direct Injection
Gasoline Direct Injection (GDI)

- Better Fuel Economy
  - Operates globally leaner (better $\gamma$)
  - Eliminates throttle plate
  - Increase in compression ratio
- CO and HC Emissions Nearly Negligible Given Proper Mixing
- PM can Become a Problem
  - Fuel spray causes rich fuel pockets
  - Analogous to direct injection CI
- $\text{NO}_x$ Issues
  - Now in lean regime of $\text{NO}_x$ production
  - Maybe cannot use TWC $\text{NO}_x$ reduction reactions (i.e. $\text{H}_2/\text{CO/HC}$ to reduce $\text{NO}_x$)

Not a new concept!
**GDI Lean Burn**

Up to 25% improvement in fuel efficiency

*Assanis, et al, ASME 2000*

*Gasoline Direct Injection (Courtesy of Mitsubishi)*
Benefits of lean burn and high pressure combustion

- Thermodynamic benefits lead us to operation with leaner mixtures, higher compression ratio and reduced pumping losses.

- Need for increased power density by turbo/downsizing is leading to higher pressure combustion.

Potential gain of 30% by lean burn at high CR for SI engines.

Automobile engines
Caris and Nelson (1959)
SAE Paper No. 590015.

natural gas engines
Diesel Engine:  

Very Efficient, Not So Clean

Thermal Efficiencies up to 55%

Plagued by the NOx-Soot tradeoff
Diesel Combustion Simulation

B. Vanzieleghem, W. Lim, D. Assanis
High Temperature Zones → NOx Formation

High Fuel Concentration Formation → SOOT

B. Vanzieleghem, W. Lim, D. Assanis
Aftertreatment Options for Diesel Exhaust

CO(NH$_2$)$_2$ + H$_2$O $\leftrightarrow$ 2NH$_3$ + CO$_2$

Urea SCR

Urea injector

DOC/DPF

LNT

HC SCR

Close coupled DOC

Fuel Post Injection

LTC Engine

Collaborative Development of Clean Diesel Exhaust Aftertreatment System

21st Century Jobs Fund Project
A Paradigm Shift Approach: Low Temperature Combustion (LTC)

Clean AND Efficient

LTC strategies ensure high efficiency, while practically eliminating NOx and soot formation.

LTC applied to gasoline engines holds promise of significantly improving fuel economy of light vehicles – by 20-25%.

Diesel based LTC is critical for meeting future emission regulation.

LTC strategies are attractive for use with alternative fuels combustion, and for stationary power applications.
When Otto meets Diesel...
When Otto meets Diesel...

- Ultra low NOx
- Ultra low PM
- High efficiency

But…
Ignition is not controllable…
Or is it??

Wooldridge et al, DOE/LTC Consortium
Comparison of SI and HCCI combustion

Spark Ignition

HCCI

Prof. Yuji Ikeda, Kobe University. Iso-octane fuel
Challenges of gasoline LTC

• Challenges
  – Must use autoignition (CI)
  – Transient control
  – NOx and knock constraints
  – Misfire and bulk quench
  – Limited range of LTC operation
  – Dual mode (SI-HCCI) engine needed
  – Kinetics for practical HC fuels at high pressures

• Possible remedies...
  – Spark assisted CI
  – Stratification
  – Boosting/downsizing
Towards future high efficient and ultra clean automotive engines

- Explore new areas and regimes of combustion that can enable future gasoline engines with 20-40% improved fuel economy.
- Enhance the physical understanding, expand the experimental knowledge base and thus develop and validate predictive modeling tools to overcome significant challenges and shorten the path to market.

Combustion implications
- High Pressure Lean Burn (HPLB) multi-mode combustion:
  - lean burn SI
  - spark assist compression ignition (SACI)
  - HCCI

UM Multi-Mode Combustion Diagram (MMCD)
Cylinder Deactivation

• Useful for reducing pumping losses
  – By reducing the number of cylinders, the remaining cylinders require less throttling to maintain same power output
  – Combustion performance and thermal efficiency may also be improved because active cylinders running at higher load have increased effective compression ratio, faster burn rate, lower relative heat losses

• Drawbacks from step change in output from turning on/off
  – Reduces frequency of torque pulsations from the spacing of the firing but can increase the amplitude of these pulsations at the crankshaft
  – Constraint of noise, vibration and harshness (NVH) on the operating limits of cylinder deactivation
  – Complexity of the controls needed along with their resulting costs can limit the practicality of the method

• A common guideline for technologies that eliminate pumping losses is that the heavier vehicles that have a higher ratio of engine size to vehicle mass are the type that respond best to its usage
  – In 2002, a National Research Council report suggested that fuel consumption can be reduced from 3-6% by using cylinder deactivation
  – Researchers have calculated that 2.4-5.0% of fuel energy used in the EPA combined cycle test goes to pumping losses
Variable Valve Events

Toyota VVT-i system for Prius utilizing Atkinson cycle

<table>
<thead>
<tr>
<th>Operation State</th>
<th>Range</th>
<th>Valve Timing</th>
<th>Objective</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>During Idling</td>
<td>1</td>
<td>EX TDC IN</td>
<td>Latest timing</td>
<td>Eliminating overlap to reduce blow back to the intake side</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BDC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>At Light Load</td>
<td>2</td>
<td>EX TDC IN</td>
<td>To retard side</td>
<td>Decreasing overlap to eliminate blow back to the intake side</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>At Medium Load</td>
<td>3</td>
<td>EX TDC IN</td>
<td>To advance side</td>
<td>Increasing overlap to improve internal EGR for pumping loss elimination</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Camless Engines

- Complete elimination of traditional pumping loop by removing throttle
  - May also allow for more air during WOT events over traditional cam systems
- Control air input by rate shaping lift profiles and timing
- Significant gain in fuel economy at part load operations
- Large cost associated with one solenoid valve let alone an entire engine
- Degrees of freedom increase dramatically becoming a calibration nightmare

Smart Valve Actuation technology: the camless engine becomes a reality
Technology Continuum

Continuously Variable Transmissions (CVT)

• Rather than having a fixed set of gear combinations, or "ratios", the CVT transmission allows an almost limitless number of engine speed to vehicle speed ratios
• This provides significant benefits over a traditional automatic transmission, including:
  – The computer can intelligently choose to have the engine and electric motor rotating at the optimal speed, regardless of how fast the car is travelling
  – Because of the smooth transition in gear ratios provided by the CVT transmission, there is a constant, seamless acceleration from a stop all the way up to cruising speed
  – The CVT transmission has a smaller power loss than a typical automatic transmission, resulting in better efficiency and acceleration
• Issues
  – People are used to the jerk associated with gear shifting
  – Pressing on the accelerator pedal will make the car move faster but it may not change the sound coming from the engine confusing drivers and leading to a mistaken impression of a lack of power
  – CVT torque handling capability is limited by the strength of their belt or chain, and by their ability to withstand friction wear between the torque source and transmission
  – CVTs are predominantly belt or chain driven and therefore typically limited to low powered cars and other light duty applications
  – Cost
Hybrid Propulsion

Parallel HEV

Series HEV

Power Split HEV

Hydraulic HV
Hybridization

• Increases Fuel Efficiency
  – Downsize ICE
    • Batteries or accumulators make up for extra power
    • May be charged continuously or when depleted
  – Run ICE at optimum settings
  – Regenerative braking re-uses previously lost energy due to friction
  – Shut-off engine at idle \( (\text{bsfc}_{\text{idle}} = \infty) \)

• Series and Parallel Arrangements
  – Both have their advantages and disadvantages
  – In general, a series hybrid is more efficient but less powerful than a parallel hybrid
Electric Hybrid Challenges

- Relative low power density of batteries (delivery of relatively low power over long time)
- Advanced controls needed for proper utilization require longer calibration times (engine + motor)
- Addition of weight will reduce fuel economy (somewhat offset by smaller engine)
- Dependence on specific user driver commands
  - People have found that the amount of fuel economy gain is subject to their driving habits
  - Power switching would be more effectively utilized if there is a closed-loop feedback to respond to user
- Cost
  - Does it make sense to add X amount of dollars for hybridization whereas it takes Y amount of dollars to run a diesel engine?
  - How many miles does it take at Z dollars per gallon to make up initial cost investment?
- Exhaust emissions may be higher

This video has no audio.

The Integrated Motor Assist System (IMA) is composed of a gasoline engine and an electric motor, and has several important functions. Located between the engine and transmission, the electric motor supplies additional power during acceleration. It also functions as a high-speed starter and as a generator for the charging system during regenerative braking.
Simulation of an Integrated Starter Alternator (ISA) System for the HMMWV

Andreas Malikopoulos, Zoran Filipi and Dennis Assanis,
SAE 2006-01-0442

• Comparison of a conventional powertrain and mild hybrid powertrain with ISA configurations:
  ✓ Real-time power management algorithm is critical for realizing the fuel economy benefits in the ISA hybrid-electric system due to the small size of the electric machine and its limited potential for regeneration.

• The application of 10 kW ISA for mild hybridization in conjunction with the power management algorithm allowed a 4.3% improvement in fuel economy:
  ✓ 48% engine shutdown
  ✓ 35% reduction in inefficient engine operating points
  ✓ 17% regeneration
Series Hybrid Electric Vehicle (SHEV)

Vehicle Specification

<table>
<thead>
<tr>
<th>Component</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle</td>
<td>20,000 kg (44,090 lbs)</td>
</tr>
<tr>
<td>Engine</td>
<td>400 HP (298 kW)</td>
</tr>
<tr>
<td>Generator</td>
<td>400 HP (298 kW)</td>
</tr>
<tr>
<td>Battery</td>
<td>18Ah / 120 modules</td>
</tr>
<tr>
<td>Motor</td>
<td>2 x 200 HP (149 kW)</td>
</tr>
<tr>
<td>Maximum speed</td>
<td>55 mph (90 kmph)</td>
</tr>
</tbody>
</table>

Framework from the ARC Case Study: Integrated hybrid vehicle simulation (SAE 2001-01-2793)
Power Management of SHEV

SOC: State of Charge

SOC high Limit
SOC
SOC low Limit
Discharge Charge Braking

Discharging Mode

Charging Electric Drive Mode

Braking Mode

Engine
Generator
Power Bus Controller
Battery
Motor
Wheel
Motor
Wheel
Hydraulic Hybrids

- Highest Possible Fuel Economy Gain
- Regenerative Braking
  - Hydraulic hybrids > 70% recovery
  - Electric hybrids < 25% recovery
- Lowest Incremental Cost
  - Shortest payback to owner
  - Highest lifetime-savings
- Ultra-low Emissions
- Enables Unique High-efficiency Engines
- Reductions in Greenhouse Gases and Imported Oil
- Technology Exists Today

Hydraulic Hybrid Challenges

- Complexity of Controlling/Drivability
  - Need appropriate response rates for torque generation and regeneration of braking energy
- Noise, Vibration and Harshness*
- Increasing Energy Density of Accumulator
  - About 4-5 kpsi currently, need around 7 kpsi for smaller vehicles
- Safety for High Pressure Storage System
- Aftertreatment
  - Highly transient operation
  - Exhaust system may be much cooler due to periodic engine shut-off
  - Cold start and transient emissions may be higher

* SAE Paper 2002-01-3128
Advanced Propulsion System Design:
Parallel/Series Electric & Hydraulic Hybrid

Zoran Filipi, Dennis Assanis, Dohoy Jung, Hosam Fathy, Huei Peng, Jeff Stein
11th ARC Conference, 12th ARC Conference, Case Study Presentation (2005& 2006)
Young Jae Kim and Zoran Filipi
SAE 2007-01-4151

- Engine-In-The-Loop simulation/experimentation with complete vehicle simulation and driver model allowed:
  - Detailed insight into real engine transients, characterization of critical conditions, and evaluation of different propulsion options
- Parallel Electric Hybrid powertrain: 18% FE improvement
- Series Electric Hybrid powertrain: 26% FE improvement (Downsized V6 engine)
- Series Hybrid Hydraulic powertrain (2 hydraulic pump/motors & sequential operation): FE improvement of 68% with engine shutdown, and 49% without engine shutdown over the FTP75 cycle.
Plug-In Hybrid Electric Vehicles (PHEV)

- PHEVs show tremendous promise but they will have an impact on the electrical grid, the environment, consumers and businesses.
  - Quantify the impact of Vehicle to Grid technologies
  - Investigate Smart Electric Grids and the effect on Plug In Hybrid Electric Vehicles (PHEV)
  - Economics, consumer preferences and habits, regulations, safety and a myriad of other forces will make or break this new vehicle technology.

- Low Carbon Electricity Generation
Renewable Fuels

• E85, Biodiesel, Fischer-Tropsch Fuels are Attractive:
  – No sulfur and can use same engine
  – Partially completes the Carbon Cycle
  – Eliminates some dependence on foreign oil
  – E85 allows for increase in compression ratio (higher octane number) and better lean burn capability
  – Fuel standards are needed
  – Energy studies needed!

• Conventional Aftertreatment is Still Needed
  – Some biodiesel studies indicate lower HC, CO and PM but higher NOx*
  – E85 can have cold start issues**

* SAE 952363; SAE 961166; Tsolakis et al., Energy & Fuels (2003)
** SAE 2006-21-0024
Hydrogen Future

- Main Issue with ICE Emissions is the use of Hydrocarbon-based Fuels
- Hydrogen as a Fuel
  - A way to achieve both emission goals because water is only byproduct
  - Can help U.S. reduce dependence on foreign oil
  - Third-most abundant element on the earth’s surface*

* Argonne National Laboratory (2003)
Hydrogen ICE

• Burn Hydrogen Directly in ICE
  – May actually be ideal fuel for ICEs because of its high efficiency and negligible aftertreatment requirements*

• Bi-Fuel Capable:
  – BMW Hydrogen 7 and Mazda RX-8 Hydrogen RE can run on both H₂ and gasoline

• Allows for Unlimited Individual Mobility of the Car While H₂ Infrastructure is Being Built

* SAE Papers 2006-01-3430, 2006-01-0430
Fuel Cells

• Replace the Combustion Engine as the Powerplant
• Nearly Twice as Efficient as a Conventional S.I. Engine

Issues
- Power density needs to be increased
- Energy density of hydrogen storage is low
- Clean source of hydrogen needed (CO poisons cell)

Burns et al., Scientific American (2002)
The Future: Sustainable Mobility

Carbon Recycling
Pathways for Carbon Neutrality

- **Energy Source**
  - Biomass
  - Low Carbon Electricity Sources

- **Carrier**
  - Liquid Fuels

- **Propulsion System**
  - Internal Combustion Engine
  - Grid Independent Hybrid
  - Plug-In Hybrid
  - Electric Vehicle

- **Technology Enablers**
  - Novel Bio-Fuel Blends
  - New Combustion Strategies
  - Aftertreatment
  - Hybrid Powertrains
  - Battery Materials
  - Thermoelectrics
  - Photovoltaics

- **Life Cycle Thrust**
  - Biofuels Thrust
  - Powertrain Thrust
  - Materials Thrust
C-Neutral Energy Systems for Sustainable Mobility

- Energy-storage Materials (batteries & fuel cells)
- Energy-harvesting Materials (light & heat => electricity)
- Biofuels

Life Cycle:
- Fuel Cycle
- Vehicle Cycle
- Tank to Wheels
- Well to Tank

Powertrains
- LTC Engine

Energy:
- Electricity
- To Household Loads
- To/from Utility Grid

Wind Turbine or Photovoltaic Array
- Array DC Disconnect
- Inverter
- AC Breaker Panel

Well to Tank
- Tank to Wheels

LTC Engine