Cooled EGR and alternative fuels

Solutions for improved fuel economy

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Motivation and Market Forces

• Emissions standards have been getting more strict on an approximately 4 year cycle
  – HD standards are less strict, but getting tighter quickly
  – Light duty standards are already fairly strict, but there is always potential for further reductions

• New concerns regarding “global climate change” and energy security have resulted in a renewed focus on fuel economy

• Customers are concerned about fuel consumption
  – Cost of gasoline is getting higher
  – Social aspects
  – CO₂ regulation increasing

• High mileage vehicles offer a significant marketing opportunity
The Route to High Efficiency

• Gasoline engines have the potential to be intrinsically more efficient than diesel engines
  – Otto cycle has significantly higher ideal efficiencies than Diesel cycle
• In the “real world” gasoline engines suffer from some drawbacks
  – Pumping losses
    • Emissions standards require TWC and a fixed A/F ratio – throttle is required
  – Knock
    • Limits compression ratio
    • Spark retard to combat knock severely reduces efficiency
    • Spark retard also increases exhaust temperatures
      – Requires overfuelling
      – Engine cannot meet emissions at high load
• 2 routes to high efficiency:
  1. Downsize and boost at “normal compression ratio”
  2. Increase compression ratio and maintain or increase displacement
A Solution for High Efficiency

• Reduce or eliminate pumping losses
  – Use cam phasing and/or hot EGR at low load to increase internal residual
  – Reduce engine displacement
    • Requires higher manifold pressures for the same torque as the larger engine

• Increase compression ratio
  – Better thermal efficiency

• Boost to increase specific power
  – Overcomes small displacement
  – Improved marginal efficiencies

Ignition and flame propagation difficult

Increased exhaust temperatures require overfuelling

KNOCK
Overcoming Obstacles to High Efficiency

- Advanced ignition systems
  - Improve EGR tolerance
  - Increase knock tolerance

- Cooled EGR
  - Reduces knock
    - Combustion phasing improves for high efficiency
    - Enables high CR and/or loads
  - Reduces exhaust temperatures
    - More effective dilution than overfuelling
    - Combustion phasing improvement also helps with combustion temperatures

- Change the chemical composition of the charge
  - $\text{H}_2$ reformer
  - Alternative fuels
Improving ignitability

Top systems to date:
- Dual fine electrode spark plugs
- High energy, long duration spark systems

Fine Iridium Electrode
- HT losses
- Required breakdown voltage

Large Gap
- HT losses
- Quenching
- Required breakdown voltage
- Flow Coupling
- EMI

Long Duration / Multiple Sparks
- Probability of ignition
- Flow coupling
- Initial flame volume
- Knock tendency
- Effect of cylinder pressure on spark event

Higher Energy Levels
- Flame kernel volume
- Secondary currents
- Proportional heat losses
- Spark “blow-out”
- Durability(?)
Ignition System Improvement at Low Loads

- Very low loads present challenges to ignition with EGR
  - High levels of in-cylinder residual
  - Relatively cooler temperatures
    - Residual
    - "Hot" EGR
    - Engine surfaces
- MS System V2.1 has the best EGR tolerance
  - Best low load EGR tolerance
  - Burn duration and stability very good

![Graph showing CoV IMEP vs. EGR percentage for different systems at 2000 rpm / 2 bar bmep and 2.4-L engine at 9:1 CR]
Burn rate improvement with new ignition

- MS system V2.1 results in faster burn rates at high and low load
  - EGR tolerance improves
  - Emissions and FE improve
  - Knock resistance improves
- Level of improvement would be greater for engines with higher levels of bulk motion
  - MS V2.1 may be able to tolerate higher levels of bulk motion than other systems
High Load Performance

- Ignition challenges at high load are different
  - Spark blow out / suppression
  - EMI
  - Pre-ignition
- MS V2.1 improves EGR tolerance at high load and reduces knock tendency
  - 20% EGR suppresses knock
  - Engine runs at or near MBT timing
- Burn rate improvement significant
- WOT fuel economy good despite low CR
Improving ignition (non-igniter hardware)

• Many other parameters can be adjusted to improve ignition
  – Increase coolant temperature
    • Hotter temperatures at compression
    • EGR mitigates knock
  – Increase compression ratio
    • Higher compression temperatures
    • EGR reduces knock
    • Also improves efficiency

• Change composition of the intake charge
  – \( \text{H}_2 \) supplementation has significant potential
    • Only small amounts required for benefit (SAE paper 2007-01-0475)
H₂ Amount and the Effect on Engine Stability

- Very small amount of H₂ necessary to stabilize engine
  - < 1 mg of H₂ stabilizes engine at most test conditions (~ 5% of gasoline mass)
  - Benefits of H₂ addition rapidly fall off at levels > 0.2 % by volume
- At high CR and high load, knock limits the benefit until high H₂ levels reached
- H₂ appears to improve stability through increased burn rates and more complete combustion

Results from SAE Paper 2007-01-0475
The Influence of H$_2$ on Turbulent Burn Rate

- Effect of H$_2$ seen in 10-90% MFB duration and spark advance
  - Biggest impact seen with initial H$_2$ addition
- H$_2$ improves apparent flame speeds
  - Larger flammability limits
  - Higher laminar burning velocities
  - Reduced quench distances

![Graph showing the effect of H$_2$ on spark advance and 10-90% MFB duration](image)

3.1 bar imep, 11:1 CR, 22% EGR

Results from SAE Paper 2007-01-0475
The Influence of H\textsubscript{2} on Emissions

- **HC emissions reduced considerably**
  - H\textsubscript{2} addition promotes post-flame consumption of HC
  - Crevice emissions reduced due to shorter wall quench distances
  - Flame propagation improved due to improved flammability limits

- **NO\textsubscript{x} emissions increase**
  - Hotter flame temperatures due to faster flame speeds
  - Still significantly reduced from no EGR case

![Graph showing percent change in ISHC and ISNO emissions](image)

**Results from SAE Paper 2007-01-0475**
The Influence of H₂ on EGR Tolerance

- H₂ constant at 1% by volume
- EGR tolerance increased significantly
  - Benefit largest at low load
    - EGR tolerance lower without H₂ at this load
    - Engine still very knock limited at high loads and high CR
    - No boost – WOT condition stops EGR sweep
- Best results in multi-cylinder engine found at 40-50% EGR

![Graph showing the influence of H₂ on EGR tolerance](graph.png)

Results from SAE Paper 2007-01-0475
Ignition Improvement Options

- Advanced igniter and coil designs pay big dividend
  - Best MS system yielded a 100% improvement in EGR tolerance
- Changing fuel composition also works well
  - Small amounts of H₂ can significantly improve performance
    - Emissions and fuel consumption are reduced
    - Engine stability improves
  - Low mass of H₂ makes reformer technology more easily packaged and less energy consumptive
  - Ethanol will improve knock tolerance
- Other techniques are proving to have some benefits
  - Increasing manifold temperatures works well
  - High CR and coolant temperatures also help
Cooled EGR for Knock Reduction

• Boosted gasoline engines are knock limited above 12-14 bar bmep (or less)
  - Significant spark retard required to prevent knock
  - Excess fuel required to reduce exhaust temperatures

• Cooled EGR can reduce knock tendency
  - Restore optimal combustion phasing
  - Allows stoichiometric combustion

• Enables aggressive downsizing (> 25%) for US market

Low speed / high load conditions
2.4-L engine @ 10.5:1 CR
Cooled EGR for Reduced Exhaust Temperatures

- All EGR conditions run at $\phi = 1.0$
- EGR reduces high load exhaust temperatures significantly
  - Cost savings potential in
    - Turbine materials
    - Exhaust valve and seat materials
    - Catalyst substrate
    - Warranty exposure
  - Also has the potential to reduce under-hood temperatures
    - Less load on heat exchangers
- Increased ability to run at high loads in drive cycle
  - Emissions compliance at high load realized
  - Greater downsizing potential
Cooled EGR at High Speed / High Load

- Fuel consumption reduced by 5-20% due to elimination of enrichment (depending on engine power and enrichment levels)
- Exhaust temperature reduced by ~100 deg C with EGR addition
- Emissions reduced significantly

→ High load / WOT may now be a potential drive-cycle operating condition for a LD automotive application
Cooled EGR at Low Speed / High Loads

- At low speeds and high loads, enrichment is not typically an issue
  - Despite high levels of spark retard, exhaust temperatures are not excessive
  - Poor efficiency is due solely to spark retard due to knock
- EGR addition reduces knock
  - Big change in BSFC
  - BSCO and BSNO are reduced significantly
Downsizing Potential

- BMEP values based on a 3 L engine (i.e. 11 bar bmep in a 3 L = 14 bar in the 2.4 L)
- Engine calibration will require a continuum of EGR temperatures for optimal performance
- Low speed, high BM EP operation enabled by knock reduction from EGR
  - Shift vehicle operation window
  - Diesel-like torque curve
- Future emissions standards will require compliance at high loads
  - Enrichment region will be eliminated or very limited

Downsizing Goal:

Run FTP at > 10 bar bmep
Idle @ 2-3 bar imep or more
Cooled EGR and High CR Operation

- Friction losses increased significantly
  - Problem worse at low loads and high speeds
- EGR reduces knock tendency enough to get near full load
  - If external boost is applied, 10-11 bar is likely

- High CR helps with EGR tolerance at low loads
  - Hotter temperatures improve stability and flame speed
  - Less internal residual

2.4-L engine @ 14:1 CR
When do we use hot EGR?

- Hot / uncooled EGR is beneficial as long as knock does not occur
  - Higher MAT increases EGR tolerance
  - Higher MAT helps charge preparation
    - CO emissions reduced over cooled EGR
    - Higher MAT promotes more complete combustion
    - Pre-heating intake air increases cycle efficiencies
- NO emissions increase slightly
  - Still below baseline / 0% EGR levels
- Substantial CO reductions
  - WHY?
- Exact cutoffs between when to use cooled or uncooled EGR TBD on engine-by-engine basis

2.4-L engine @ 9.0:1 CR

- Heat Lost to Exhaust [kW]
- Incomplete combustion loss [kW]
- CoV imep [%]
- BSCO [g/kWh]
- BSNO [g/kWh]
- BSHC [g/kWh]

2500 rpm / 6.7 bar bmep
HEGR  CEGR

2.4-L engine @ 9.0:1 CR
CO reductions with EGR

- CO emissions are lower with EGR in almost all applications
- With H-EGR, part of the reduction in CO emissions may come from improved vaporization / charge preparation
- At high loads, MAT is controlled by aftercooler
  - No temperature differences between EGR condition and baseline conditions
  - CO emissions still decrease
- Simulations using CEA code indicate that lower temperatures due to dilution result in less CO emissions
  - Occurs with several diluent types
  - Very strong temperature effect
  - Lower temperatures reduce dissociation
- Unanticipated benefit of EGR use
The Path to Fuel Economy: High CR versus High Load?

- Question: What is the most effective way to improve drive cycle efficiencies?
- High CR
  - Offers theoretical advantages in thermodynamic cycle efficiency
  - High load becomes difficult
    - BSFC penalty due to spark retard is high
  - Low load performance usually improved
  - May be best for NA / low boost applications

- High Load
  - Low CR (10<CR<12) with radical downsizing
  - Allows MBT timing at very high loads
  - Marginal efficiencies become very high
    - Friction and pumping as a % of fuel energy → 0
  - Reduces or eliminates low BMEP operation
Cooled EGR

• Cooled EGR improves fuel economy
  – Knock reduction leads to improved combustion phasing
    • Reduced fuel consumption
    • Reduced exhaust temperatures
  – Diluent effect of EGR reduces exhaust temperatures
    • Reduces requirement for overfuelling
    • Engine becomes emission compliant over entire performance map

• Cooled EGR helps with emissions
  – CO and NO emissions reduced with lower combustion temperatures
  – Ability to run stoichiometric over full performance map makes engine fully emissions compliant

• Cooled EGR with moderate compression ratio enables radical downsizing (> 40%)
  – Efficiency benefits of EGR + Boost outweigh the benefits of very high compression ratio
Alternative Fuels

- **HEDGE and ethanol**
  - EGR can further improve ethanol operation
    - Further increase knock resistance
    - Reduce pumping losses
    - Hot EGR can increase MAT to help with fuel preparation issues
  - Improved ignition system can benefit ethanol operation
    - CS benefits
    - With or without EGR

- **Limited HEDGE technology can enable more efficient flex-fuel vehicles**
  - SwRI has applied for a patent under the HEDGE program
  - Enable engine optimization for E100 / E85 fuel
  - Protect for E0 operation with EGR

- **Will also work for other alternative fuels**
BMEP Limit Comparison (CR=11:1, Φ=1)

- Exceeded BMEP target with E50 and E85 without EGR
- Exceeded BMEP target with 100 RON + EGR
- BMEP target NOT met with 92 RON due to engine knock and combustion stability limits
- BMEP target was met with 92 RON + EGR + H₂ (60% increase)
- EGR alone extended knock limit by ~20% for gasoline fuels
BTE Comparison (CR=11:1, $\Phi=1$)

- BTE for ethanol blends exceeded 38%.
- 100 RON + EGR achieved target BMEP at 37.3% BTE.
- 92 RON + EGR + H$_2$ achieved ~30% BTE: Lower BTE due to retarded spark timing and losses due to reforming the fuel.
- 92 RON + EGR operated at > 35%, but not at target BMEP: Enrichment may be used to increase knock limited BMEP.

NOTE:
The amount of fuel required to make the H$_2$ was accounted for in BTE and BSFC comparisons – Assumed an ideal fuel reformer.
Comparison to Baseline

- **Baseline Data**
  - CR=9:1
  - Turbocharged
  - WOT
  - To meet target BMEP
    - Spark retard for knock
    - \( \Phi > 1 \) due to PTT limit

- **Test Data**
  - CR=11:1
  - Supercharged
  - WOT
  - To meet target BMEP
    - Spark retard for knock
    - \( \Phi \) held to 1
Comparison to Baseline

- E85 + EGR was 9% higher than baseline even though the LHV of E85 was 25% lower than gasoline
- 92RON + EGR + H₂ improved fuel consumption by 8%
- 100RON + EGR improved fuel consumption by 19%
- Fuel consumption difference between 100RON and E85 was proportional to difference in LHV
Result with Ethanol and EGR

- Test engine could operate as an E85 flex fuel engine with CR = 11:1
  - Premium required EGR to meet target load
  - Regular required EGR and H₂ addition to meet target load
- EGR improved fuel consumption and emissions with ethanol blended fuels
- Increasing CR and employing EGR improved engine performance and emissions compared to base engine operating on gasoline
  - NOₓ and CO were significantly reduced
  - Full load fuel consumption with regular gasoline was estimated to be 8% lower with EGR and H₂
  - Full load fuel consumption was only 9% higher with E85 (EGR, CR=11:1) than base engine (No EGR, CR=9:1) despite 25% lower LHV
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Emissions Regulation History and Technology Solutions

Turbocharging
Intercooler

High Pressure Injection
Electronic Fuel Injection

Improved Combustion & Retarded Timing

EGR Systems
PM Traps

U.S. Heavy-Duty On-Road – Emissions Regulations Increasingly Difficult to Meet
Emissions Regulation History and Technology Solutions

U.S. Light-Duty Emissions Regulations Toughest Anywhere

Non-Road Stds Introduced

Marine Engine Stds Introduced

Comprehensive regulation of heavy-duty vehicles and their fuels as a single system. Stringent limits on NOx and particulate matter, fuel sulfur limits lowered to 30 ppm for gasoline and 15 ppm for diesel fuel.

Sulfur Content of Diesel Fuel Limited

Pb Limited to 0.05 g/gal

Oxidation Catalyst

RVP Reduction

RFG Phase I Benzene, Toxics, O2, Sulfur, RVP

RFG Phase II

Close-Coupled Catalyst Plus Underbody

EHC HC Trap, Burner, Heat Storage, Lean NOx

Honda Insight First Hybrid On Sale in U.S.

On-Board Refueling Vapor Controls Phased In

On-Board Diagnostics

Engine Control Algorithms Imposed

Pd Only

EGR, Timing, A/F Ratio, Air Pump

O2 Sensor Throttle Body Fuel Injection

Programs Required Electronic Engine Controls in Polluted Areas

Inspection and Maintenance M.P.F.I.

Evaporative Controls PCV

Vacuum Delays, Timing

3-Way Catalyst

Oxidation Catalyst

Thermal Reactor

Unleaded Introduced

Oxygenates (MeOH) 0.5 g/gal Pb

MTBE 0.1 g/gal Pb

RVP Limits

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Inspection and Maintenance M.P.F.I.
Include Fuel Economy and the Problem is Clear

http://www.sanantoniogasprices.com/retail_price_chart.aspx

Fuel price is increasing and highly volatile
CO2 Review

- Europe CO2 Regulations
  - Europe sets CO2 goals for near future
    - 120 g/km maximum CO2
- U.S. Supreme Court ruling
  - U.S. EPA should consider CO2
  - Likely that CO2 regulation will occur in U.S.
  - U.S. President reveals plan to pursue CO2 reduction
    - Asks EPA and DOE to work together for CO2 reduction

From SwRI Consulting Service Report:
Climate change awareness is intensifying in the US. The recent Supreme Court decision ordering the EPA to take action to reduce GHG emissions from vehicles lags state actions which are already moving ahead with their own low-carbon vehicle rules, potentially leading to a GHG policy “mess”. To avoid that, the US president ordered EPA, the Department of Transportation, the Department of Energy and the Department of Agriculture to propose and finalize new regulations by the end of next year that would respond to the Supreme Court order. As a starting point for such new regulation, the president proposed a 20% cut in gasoline consumption by 2017, which would force 35 billion gallons of renewable and other fuels into the US motor fuel pool by 2017. According to an environmental law specialist, the “mess” involves regulation, litigation, and Congress trying to figure out GHG legislation and how the transportation sector fits in. According to him, the ideal solution would be for Congress to take action, eliminating states from the equation. (WRFT 23-05-07)