Ultra-High Efficiency Spark Ignition Engines
For Methanol Powered Heavy Duty Vehicles In China

Leslie Bromberg
Daniel R. Cohn
MIT Energy Initiative
Massachusetts Institute of Technology

April 5, 2013

Supported by Arthur Samberg Energy Innovation Fund
Most Efficient Engines Using Most Efficiently Produced Alternative Liquid Fuel

- Methanol is the liquid fuel that is most economically and efficiently produced from coal (and also from natural gas and waste)
  - Coal-derived methanol is being rapidly introduced in light duty vehicles in China because of lower cost than gasoline
- Optimized use of special properties of methanol provide substantially more efficient engine operation
  - 20-25% higher efficiency than diesel engines
- Need high-pressure engine block
Cost Savings From Ultra-high Efficiency Methanol Engine In Heavy Duty Vehicles

1. Lower fuel cost (on energy basis) than diesel
   – Protection against increase in world-wide price of diesel
2. Lower fuel use due to higher efficiency (on an energy basis)
3. Cleaner vehicles (lower PM and NOx)
4. Much lower engine system cost (engine plus exhaust treatment) than diesel engine
   – Lower cost fuel injection system
   – Substantially lower cost exhaust treatment system than diesel for meeting PM and NOx emissions reduction regulations
   – Engine system cost could be reduced by 40%
Features That Enable Ultra-High Efficiency

1. Efficiency gain from high compression ratio, highly turbocharged and downsized spark ignition engines enabled by exceptionally high octane of methanol
   – Provides same efficiency as diesel engine

2. Additional efficiency gain from exhaust heat driven reformer
   – Reformer converts methanol into hydrogen-rich gas that is then combusted in engine. Hydrogen-rich gas has higher energy content than methanol

3. Two embodiments for further efficiency gain
   – Hydrogen-rich gas used to enable lean burn or heavy EGR at low torque, thereby increasing engine efficiency (cars, short haul trucks)
   – Hydrogen-rich gas used in alcohol Rankine cycle for greatly increased heat recovery (long haul trucks)
Reformer Exhaust Heat Recovery
And Ultra-Lean or Heavy EGR Operation

• Use in short haul trucks
• Exhaust heat driven reformer converts methanol into hydrogen-rich gas at low loads
• Recovery of heat from exhaust increases fuel use efficiency by 10%
• Hydrogen-rich gas enables ultra-lean or heavy EGR operation at low loads and enables another 10% increase in efficiency
• Methanol is used at high loads to prevent knock
Ultra-High Efficiency Methanol Engine
Methanol Rankine Cycle

- Use for long haul trucks
- Innovation: use the fuel (methanol) as the fluid, and expand/combust in the engine.
  - Eliminates condenser and turbine in conventional Organic Coolant Rankine (OCR) cycles
- Can recover most of the energy in the exhaust and re-use it in the engine!
- MIT developing compact HX/Reformer
# Ultra-High Efficiency Methanol Engines for Heavy Duty Vehicles (US Fuel costs)

<table>
<thead>
<tr>
<th>Reformer + lean burn engine</th>
<th>Alcohol Rankine Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short haul heavy truck</td>
<td>Long haul heavy truck</td>
</tr>
<tr>
<td>20% more efficient than diesel engine</td>
<td>20% - 25% more efficient than diesel engine</td>
</tr>
<tr>
<td>$7000 lower cost than diesel vehicle</td>
<td>Relative to diesel vehicle: lower vehicle cost if recovered energy used in engine; $15K additional cost if turbine is used</td>
</tr>
<tr>
<td>$5000/yr fuel cost savings</td>
<td>$12000/yr fuel cost savings</td>
</tr>
</tbody>
</table>

**Preliminary Illustrative incremental vehicle cost and fuel cost savings**

Fuel cost savings due to efficiency gain only. Assumed methanol cost is $4 per diesel equivalent gallon. Additional fuel cost savings can be provided by lower fuel cost of methanol. (In China, methanol is 25% cheaper than diesel on an energy basis)
Modification Of Diesel Engines

• Diesel engines can be readily modified to spark ignition engine by placing spark plug where diesel fuel injector is located.
  – Port fuel injector is placed in manifold

• This modification approach is being used to convert diesel engines to spark ignition natural gas engines in the US
  – Factory and aftermarket modifications
MIT Reformer/Heat exchanger

• Porous metal HX: COMPACT!
• Nickel or copper/coated by appropriate materials
• Reformer catalyst:
  – Cu-Cr-Mn (methanol → 2H₂ + CO at 100 C – 400 C)
    Yoon, Alcohol Dissociation Process for Automobiles, US patent 4444158
  – Ruthenium (methanol + water → 3 H₂ + CO₂ at ~ 100 C)
    M. Nielsen, E. Alberico, W. Baumann et al., Low-temperature aqueous-phase methanol dehydrogenation to hydrogen and carbon dioxide, NATURE 495 7 MARCH 2013, pg 86
  – Cu Zn Al Zr catalyst on a Cu Zn foam (methanol + water → 3H₂ + CO₂ at 250 C)
Summary

• Ultra-high efficiency spark ignition methanol engines in heavy duty vehicles can provide substantial cost savings, meet the most stringent air pollution standards and improve energy security

• We are interested in working with Chinese companies who would like to explore the ultimate potential of methanol
### Ultra-High Efficiency Light Duty Vehicles

<table>
<thead>
<tr>
<th>Conventional engine block</th>
<th>Stronger block</th>
</tr>
</thead>
<tbody>
<tr>
<td>Port fuel injection (PFI)</td>
<td>Direct injection (DI), Turbo</td>
</tr>
<tr>
<td>30% more efficient than gasoline PFI</td>
<td>30% more efficient than gasoline turbo DI (45% more than gasoline PFI)</td>
</tr>
<tr>
<td>$500 - $700 extra vehicle cost</td>
<td>$500 - $700 extra vehicle cost relative to gasoline turbo DI</td>
</tr>
<tr>
<td>$400 - $600/yr fuel cost savings</td>
<td>$300 - $450/yr fuel cost savings relative to gasoline DI turbo</td>
</tr>
</tbody>
</table>

Preliminary Illustrative incremental vehicle cost and fuel cost savings

Fuel cost savings due to efficiency gain only. Assumed alcohol cost is $4/gge, same as gasoline. Additional fuel cost savings likely from lower fuel cost of methanol.
Flex-Fuel Operation Of Ultra-High Efficiency Light Duty Vehicles Powered By Methanol

- When methanol is not available, the vehicle can be operated almost entirely on gasoline with a 10-30\% efficiency gain relative to a conventional gasoline engine (naturally aspirated, PFI)

- This is accomplished by on-demand octane boosting from a secondary tank that contains high concentration methanol (externally filled or provided by onboard separation of M15)