Hydraulic Hybrids

EPA Hybrid Truck Initiative

October 17, 2006

Charles L. Gray, Jr., Director
Advanced Technology Division
Office of Transportation and Air Quality
U.S. Environmental Protection Agency

Clean Automotive Technology
www.epa.gov/otaq/technology
Likely World Oil Production

- Already Consumed
- Proven Reserves (EIA) →95%*
- Double Proven Reserves →50%*
- Triple Proven Reserves →5%*

* Probability

Demand assumes EIA’s growth rate of 1.9%
WHEN (not if) Does the GAP Start?

Projections for World Crude Oil Demand versus Supply

Gap must be met by:
- Increased MPG
- Alternative Fuels
- Reduced VMT

| Already Consumed | Proven Reserves (EIA) | Double Proven Reserves |

Million Barrels per Day

2000 2020 2040

2007 ?

2016 ?

1X

2X
New Opportunities

There is a growing need for improved efficiency and alternative fuels.

Projected Demand Un-Met by Petroleum

2 million barrels per day of petroleum equivalent → ~60 billion gallons per year of Methanol

[~210 MMT - over 5 times current world demand]
Impact on US Economy?

Total Cost of U.S. Imported Crude Oil

Est. Price per Barrel

Spot Price Now is between $60 to $70

Avg Price for 2005

More?

$500 B

$400 B

$300 B

$200 Billion So Far!

Future estimates account for VMT increases.
Gap Must Be Met By:

**Alternative FUELS**
Renewable to the extent possible, low cost, and sufficient resource base to sustain demand

**Increased mpg POWERTRAINS**
Exciting to the consumer, and simultaneously, ultra-efficient and low cost

**Fuels**
- Low Sulfur Gasoline
- Low Sulfur Diesel
- Bio-Diesel
- Fischer-Tropsch Diesel
- DME (Dimethyl Ether)
- **Methanol**
- Ethanol
- Natural Gas/CNG/LPG
- Electricity
- Hydrogen

**Engines**
- Gas Engine Improvements
  - Clean Diesel
  - Variable Displacement
- Variable Compression
- DI Gasoline
- **HCCI engine**
- Alcohol engine
- Fuel Cell
- **Free Piston Engine**
- HyTEC

**Drivetrains**
- CVT
- Electric Hybrids
- **Hydraulic Hybrids**
INCREASED MPG

Cost-Effective Powertrains

Current HEVs

Current EPA Demos

SUV Mechanical
- Clean Diesel
- Var Disp Conv Gas
- Var Disp Clean Diesel
- SUV HHLA - Engine on
  - Conv Gas
  - Clean Diesel
  - Var Disp Conv Gas
  - Var Disp Clean Diesel
- SUV HHLA - Engine off
  - Conv Gas
  - Clean Diesel
  - Var Disp Conv Gas
  - Var Disp Clean Diesel
- SUV SHHV - Engine on
  - Conv Gas
  - Clean Diesel
  - Var Disp Conv Gas
  - Var Disp Clean Diesel
- SUV SHHV - Engine off
  - Conv Gas
  - Clean Diesel
  - Var Disp Conv Gas
  - Var Disp Clean Diesel

*minus lifetime brake savings
EPA Priorities for Clean Automotive Technology

Revolutionary Engines

Revolutionary Drivetrains

Ultra-Clean & Ultra-Efficient Vehicles

Focusing on unique, cost-effective technology

- Achieve ultra low pollution emissions
- Increase fuel efficiency
- Reduce greenhouse gases

Technologies with high potential for commercialization to deliver real-world results!
INCREASED MPG

Why Hydraulic Hybrids?

- Highest possible fuel economy
- Lowest incremental cost
  - Shortest payback to owner
  - Highest lifetime-savings
- Ultra-low emissions
- Enables unique high-efficiency engines
- Greater reductions in greenhouse gases
- Greater reductions in imported oil

Vehicle technologies that deliver real-world results cost-effectively!
Hydraulic Hybrid Technology is Scalable for All Vehicle Types

- Hydraulic Hybrid technology is suitable for all vehicles
  - Passenger cars → Large SUVs/Pickups
  - Class 3 Work Trucks → Class 7/8 Trucks

- **In the 1990’s** - EPA focused its initial research efforts on large cars

- **Now** - EPA is focusing its initial technology transfer efforts on urban deliver vehicles (200,000+ sales per yr)
EPA Hydraulic Hybrid Timeline

**Electric Hybrids**

- Intense research program to study hydraulic hybrid technology and systems

**SUVs and LDTs:** Ford F-550 and Excursion (launch assist), GM Suburban and Ford Expedition (series)

**Full Series – Red Ford Expedition**

**Full Series – UPS Package Car**

**Chassis 6 – Taurus size**

Ways to Increase Average Vehicle Efficiency...

1. Capture and re-use energy lost to friction braking
   ✓ Regenerative Braking

2. Improve average efficiency of the engine / drivetrain
   ✓ Shutoff engine at idle
   ✓ Operate engine at “sweet” spot
   ✓ Shutoff engine at all times when not needed

3. Reduce the energy needs at the wheels
   ✓ Reduce Aerodynamic Drag
   ✓ Reduce Rolling Resistance
Regenerative Braking

**Hybrids try to recover this energy**

Where Does the Energy at the Wheels Go?

EPA City Cycle Energy Delivered to the Wheels
(Baseline- 20000 lbs, vt365)

- Energy lost to Friction brakes: 40%
- Energy consumed by Rolling Resistance: 31%
- Energy consumed by Aero Drag: 29%

Hydraulic Hybrids: >70%

Electric Hybrids: <25%

EPA Highway Cycle Energy Delivered to the Wheels
(Baseline- 20000, vt365)

- Energy lost to Friction brakes: 9%
- Energy consumed by Rolling Resistance: 29%
- Energy consumed by Aero Drag: 62%

Hydraulic Hybrids: >70%
Efficiencies While Braking/Accelerating Hydraulically

Data Typical for a Class 6 Delivery Truck

Regenerating Mode

Pump Mode (93%)

Motor Mode (92%)

Hydraulic Storage System (97%)

Accumulator

Reservoir

Hydraulic Pump/Motor

Energy Returned To Wheels

80

86

77.6

71

86

-14

Friction Braking & Drag and Driveline Losses

Vehicle Kinetic Energy

Braking Event
35-0 mph, 0.1 g

Energy Returned To Wheels

71

Acceleration Event
0-35 mph, 0.1 g

Analysis courtesy of Automotive Research Center – University of Michigan
1. **Specific Power:** ~ 7 kw/kg
2. **Specific Cost:** $9/kg

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**Hydraulic Hybrid Accumulators**

1. **Charge/discharge cycle efficiency:** 95-99%
2. **Specific power:** High pressure accumulator (with oil that transfers the power/energy) can deliver very high specific power in excess of 3 kw/kg
3. **Energy density:** >50 kw-sec/gal
4. **Specific energy:** ~8 kw-sec/kg
5. **Specific costs:** $10/kg

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**Integrated Bent-Axis Hydraulic Pump-Motors**
EPA Gen 2 Bent-Axis Pump-Motor

Hydraulic Fluid Inlet/Outlet
Actuator
Input Shaft
Case
Case Cover
EPA Gen 2 Bent-Axis Pump-Motor

- Input Shaft
- Flow Passages
- Trunnion
- Yoke
- Back Plate
- Spool Valve
- Actuator
Efficiency Comparison of Current versus Advanced Pump-Motors

Rexroth A6VM107
Total Efficiency
3000 PSI

EPA GEN I 110 cc/rev
3200 PSI
Motor Mode

90%
95%
90%
95%
Parallel Hydraulic Hybrid Operation

Illustration courtesy of Automotive Research Center – University of Michigan
Series Hydraulic Hybrid Operation

Illustration courtesy of Automotive Research Center – University of Michigan
How Full Series HHVs Work

**Mode 1 – Braking**
Saving Energy Normally Wasted While Braking

**Mode 2 – Initial Acceleration**
Uses Only Stored Power

**Mode 3 – Sustained Acceleration**
Uses Engine and Stored Power

**Mode 4 – Cruising**
Uses Only Stored Power

**Mode 5 – Extended Cruising**
Uses only Engine Power*

* (Excess engine power goes to the high pressure accumulator)
Hydraulic Hybrids Efficiency

Parallel versus Series

Series hybrid designs enable the next step in hybrid design – big opportunities for:

- More efficient engine operation, and
- Unique, even more cost-effective engines
- Higher fuel economy with less incremental cost

<table>
<thead>
<tr>
<th>Hybrid Configurations</th>
<th>Vehicle Fuel Economy Improvement</th>
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<tbody>
<tr>
<td><strong>Mild</strong> Hybrid (parallel, launch assist with conventional engines)</td>
<td>20-40%</td>
</tr>
<tr>
<td><strong>Full</strong> Hybrid (series) with conventional engines</td>
<td>60-80%</td>
</tr>
<tr>
<td><strong>Future Full</strong> Hybrid (series) with advanced engines, improved aerodynamics, and tires</td>
<td>100-120%</td>
</tr>
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## Comparison of Parallel versus Series Configurations...

<table>
<thead>
<tr>
<th></th>
<th><strong>Parallel Hybrid</strong></th>
<th><strong>Series Hybrid</strong></th>
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</table>
| **Pros**         | ✓ Appears more cost effective than electric alternatives  
                   ✓ Good place to get experience with hydraulic drive components  
                   ✓ Conventional drivetrain still available for backup | ✓ Most cost effective option  
                   ✓ Allows optimum engine operation for efficiency and emissions reductions  
                   ✓ Approach has been standard in off-road equipment |
| **Cons**         | ✓ Analysis indicates good, but less attractive pay back when compared to series | ✓ Somewhat higher risk with new drivetrain components |
## Advanced High Efficiency Engines Enabled by Series Hydraulic Hybrids

### High Efficiency Gasoline HCCI
- Homogenous Charge Compression Ignition
- Diesel efficiency levels from gasoline (Tier2 bin 2 emissions)

### Direct Hydraulic Power
- High efficiency hydraulic power directly from a free piston engine – no crank

### Thermal Energy Recovery
- Recovers energy from engine exhaust heat
- Fuel cell efficiency at 1/5 the cost
- Works best with Methanol

### Complete Variable Displacement Engine
- Twin Crank engine to maximize engine efficiency yet have peak power available on-demand

### Alcohol Engine
- Diesel efficiency levels from Ethanol or Methanol
INCREASED MPG

Engine Power versus Time

![Graph showing engine power versus time with vehicle speed in the background. The graph compares drive power (kw) over time (seconds) for conventional and full series hybrid vehicles.]
Engine Map for a Typical Engine

Areas of primary operation

- Best Efficiency
- OK Efficiency
- Poor Efficiency

- Conventional Vehicle
- Full Series Hybrid

- Areas of primary operation
EPA Hydraulic Hybrids

*Historic Test Demo Chassis*

- Full Series Hydraulic Hybrid
- 80+ mpg combined city/highway mpg
- ~8 seconds 0-60 acceleration time
- No need for expensive lightweight materials (test weight 3800 lb)
- Led the way for subsequent demonstration vehicles like Sport Utility Vehicles and commercial urban work trucks
Urban Delivery Truck – Historic Parallel Hybrid

Hydraulic Assist Hybrid

- Demonstrates the ease of retrofitting trucks with hydraulic hybrid technology
- Shows ability to get low hanging fruit (20-30% mpg improvement)
- Gold award for mpg improvement and Silver award for performance at the 2003 Michelin Bibendum Challenge
Status of EPA’s Parallel Efforts

- Completed technology transfer on parallel hydraulic hybrids
- Eaton has a successful “HLA” system
- We are now focusing exclusively on series hydraulic hybrid designs to gain full benefits
EPA’s Full Series Hydraulic Hybrid SUV Demonstration Vehicle

Communicates a Vision of “Production Potential” for SUV’s and Light Trucks

- Diesel & 4-WD hydraulic hybrid (”HH”) shows 85% fuel economy improvement & better acceleration
- $2200 incremental cost add for diesel engine and hydraulic hybrid technology means excellent 1-2 year payback for consumer (assumes high volume)
Integrated Design...

View from Rear

Engine Pump

Integrated Front Drive

Integrated Rear Drive w/ 2-speed Trans
**Establish BEST POSSIBLE Business Case for UDV Hybrids**

1. **Fuel Economy Increase**
   - 60-80%

2. **Incremental Cost for Hybrid Systems**
   - 10-15% of base vehicle cost
   - (high volume)

3. **Payback Period**
   - 2-3 years

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**EPA is focusing its efforts on full series “hydraulic” hybrid designs to meet these goals**
**EPA’s Full Series Hydraulic Hybrid Urban Delivery Vehicle**

Hydraulic Hybrid
UPS Package Car Demo
Creates Visibility With “Real World” Experience

- 60-70% mpg improvement in city driving
- 2-3 year payback has attracts attention from fleets
- Potential for net Lifetime savings over $50,000 with $2.75/gal fuel costs
- Demonstration to accelerate technology transfer to industry & familiarity with technology
- Partners (UPS, Eaton, International Truck, U.S. Army)

New York Times (Feb 10, 2005) – “The Environmental Protection Agency and the United Parcel Service announce a test project today demonstrating a new type of transmission that could save energy and reduce pollution.”
Concept Vehicle Layout
Configuration for UDV#1

- Engine
- Pump
- Rear Hydraulic Drive
- Fuel Tank
- Muffler

Viewed from top of chassis

Rear Hydraulic Drive
# UDV#1 Overview of Initial Lab Dyno Fuel Economy Test Results

<table>
<thead>
<tr>
<th></th>
<th>MPG</th>
<th>Increase</th>
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<tr>
<td>Baseline Vehicle</td>
<td>10.4</td>
<td></td>
</tr>
<tr>
<td>HHV – engine always on</td>
<td>14.4 - 15.0</td>
<td>39-44%</td>
</tr>
<tr>
<td>HHV - engine-off</td>
<td>15.8 - 16.5</td>
<td>52-59%</td>
</tr>
<tr>
<td>(when vehicle is not moving)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HHV – more engine-off</td>
<td>17.8 - 18.1</td>
<td>70-74%</td>
</tr>
<tr>
<td>(when decelerating and when vehicle is not moving)</td>
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UDV#1 Integrated Rear Drive

Primary Rear Drive Used to meet basic driving requirements

Both are integrated into rear differential

Auxiliary Rear Drive Needed to meet 29.5% grade requirement

Rear of Vehicle
Primary Rear Drive Assembly
Hydraulic Hybrids Show Promise, Toyota Says

Eric Mayne
Ward's AutoWorld, May 1, 2006 12:00 PM

As auto makers struggle to design more efficient batteries — key components in hybrid-electric vehicles — hydraulic hybrid technology is getting a second look.

Hydraulic systems are "showing efficiency numbers better than you get with batteries — a lot better," says David Hermanoe, executive engineer-environmental engineering at Toyota Technical Center, U.S.A., Inc.

"If, in volume production, those prove out to be reasonable numbers, then maybe you start looking seriously at how would I package it?"

Packaging has been the bane of hydraulic hybrid technology because, to date, such systems require large cylinders to store the required energy. For this reason, heavy-duty vehicles have been the testing ground for hydraulic systems.

Recently, China Daily reported a fleet of 50 hydraulic hybrid buses were ready to hit the streets of Beijing. Last year, the Environmental Protection Agency agreed to work on a hydraulic hybrid UPS truck with Eaton Corp., which previously had outfitted a garbage truck with such a system.

"They work really best as garbage trucks because that duty cycle really, really, really has lots of high-power pulses and lots of high-power discharges during acceleration," Hermanoe says. "And the hydraulic systems are really good at that. There are challenges with packaging hydraulic systems in a small vehicle. Will we see them in smaller vehicles? Maybe."
“HHV Is Beijing’s Choice” Said China Daily, The Biggest English Newspaper In China

New buses could help Beijing cut fuel intake
Guan Xiaofeng
2006-01-03 08:35

As part of Beijing’s effort to cut down fuel consumption and reduce emissions, 50 energy-efficient buses using hydraulic hybrid technology will soon be experimentally operating throughout Beijing’s streets.

If the plan proves successful, the new technology could be introduced to all the city’s buses, said an official with the Beijing Municipal Commission of Development and Reform.

Although the experimental operation might last for one to two years, commission official Zhang Yanyou estimates it will take less than one year to reach a decision.

Huang Qian, another official with the commission, said the breakthrough in hydraulic hybrid vehicles (HHV) technology is major for Beijing, which is prioritizing development of public transport as the main way to ease its increasing traffic pressure.

“Beijing has been chosen by the central government as a pilot study in the formation of a circular economy,” Huang said. “The introduction of energy-efficient buses is part of our efforts to build a resources-saving and environment-friendly metropolis.”

Beijing has now 18,000 buses running on the road, according to the city’s traffic management bureau.

HHVs can save more than 30 per cent of fuel consumption and reduce 20 to 70 per cent of emissions, said Hu Shenglong, vice-president of the Beijing-based Chargeboard Electric Vehicle Co, Ltd, which develops the technology.

HHVs have special devices to absorb and deposit energy in the process of braking and release the energy when the vehicles restart or speed up, said Hu.

As a result, HHVs can serve as city buses because they experience frequent braking and restarting.

The hydraulic devices can be added to the chassis of all types of vehicles without changing their structures or engines.

The private high-tech company is the first Chinese company to develop the technology and grasp full intellectual property rights, Hu said.

It has been applied to the buses in some of China’s airports and attracted interest from several major bus companies and manufacturers in the nation.

Last year, the company signed a contract with the Beijing Bus Company to jointly promote the technology in the city.

Zhang said the government would financially support the development of HHV technology in the initial stage and provide a platform for its industrialization.

After implementation in Beijing, Zhang said he hopes the HHV buses can be introduced to other parts of the country.

Earlier this year, the municipal government announced it would renew about 8,000 buses by the 2008 Olympic Games.

HHVs are just one of the type of energy-efficient vehicles promoted in China. The other types include: hybrid electric vehicles, fuel cell vehicles and pure electric vehicles.

(China Daily 01/03/2006 page3)

Content: http://www.chinadaily.com.cn/english/doc/2006-01/03/content_508758.htm
What Others are Saying...

- **Administrator Steve Johnson, EPA** This fuel efficient technology doesn't just make sense for our environment and our energy security, it makes sense for our wallets, because the hydraulic hybrid system on this UPS vehicle is incredibly cost-effective. Today we are seeing that energy innovation solutions like the hydraulic hybrids can power our nation’s economy and drive our environmental success. …America is too dependent upon foreign energy, and the best way to jump off that treadmill of dependency is through innovative technology like we have here today.

- **Congresswoman Tubbs-Jones** It is opportunity for government and private business and industry to work together to make a difference on behalf of all the people regardless of where we come from, regardless of our party. It is about trying to make a difference using new technology and have an opportunity to move forward.

- **Congressman Rahm Emanuel** You know, this is truly a “hat trick”, you don’t get many of those in government, or in public policy. This is a good economic policy. This is a good energy policy. And, this is a good national security policy.

- **Congressman Mark Souder** Having the EPA work with American based companies to lead the world in this type of industry is very important, not only for the environment, not only for energy, but for American workers.

- **Senator Mike Dewine** Somebody is going to develop the technologies and we are either going to be buying it from the Germans, Japanese or the Chinese, or we are going to be selling it to them. What we see here today is an example of where we are selling and where we are developing and where America technology is leading the way.

- **John Beystehner, COO UPS** The hydraulic hybrid technology is quite promising and we’re eager to see how the vehicle performs in a real-world setting. We believe the impact of this initiative will go far beyond our industry.

- **Alexander M. Cutler, CEO Eaton Corporation** Eaton is proud to be working with the EPA and our industry partners in bringing this leading-edge technology to market. Innovative technologies such as the hydraulic hybrid truck represent Eaton’s focus on energy management, market-leading products and environmental responsiveness.

- **Craig Arnold, President Eaton Fluid Power** We think that based upon what we have learned over the years in terms of hydraulic technology and reliability that we have a real winner here.

- **Dee Kapur, International President-Truck Group** The diesel hydraulic hybrid concept has the potential to offer our truck customers something very unique — performance and near zero emissions with dramatic improvements in fuel economy.
The Stage is Set...

- Provides rational business case
  - Significantly reduce fuel consumption
  - Significantly reduce GHGs
  Offers a great economic incentive to quickly upgrades fleets to new clean engine technologies (lower NOx & PM)

- Technology exists today
  - No additional breakthroughs needed
  - Greatest potential for low cost

- The need has never been clearer
  - High world oil prices
  - GHGs
  - National and global awareness – everyone is looking for cost-effective solutions

We can help bring about change, quickly!
Simpler Proposed Layout for Pre-Production UDVs

- Primary Drive Assembly
- Single Steel LP Reservoir
- Single Cooling Fan
- Engine-off Power Steering
- Low Pressure Reservoir
- Engine-off Power Brakes
- Auxiliary Drive Possibly Optional
- Single 34-54 Gallon Carbon Fiber HP Accumulator
- Pump-Motor
It’s All About the Economics...

- Very strong hybrid BUSINESS CASE has emerged
  - Concept vehicle built and works
  - Alpha customer close to ready to buy
  - Tax incentives exist to support initial growth
  - Need grants assistance with pre-production
  - U.S. based

- Lower Operating Costs
  - 40% lower fuel costs
  - 75% lower brake maintenance costs
  - Potential for $7,000 incremental costs (high volume)
  - Potential for over $50,000 in lifetime savings

Fleets are willing to consider pilot programs.
Timeline to Production

------------------- Concept Vehicle ------------------
☑️ Summer ‘06 – Deal with engine-off operation issues
☑️ Fall ‘06 – UPS field test UDV#1
☑️ Fall ‘06 – Specify pre-production vehicle

--------------- Pre-Production Vehicle ---------------
☐ Fall ‘06 – UPS order 2-10 production prototype vehicles
☐ Summer ‘07 – Deliver production prototype vehicles
☐ Fall ‘07 - Fall ‘08 – UPS field tests

------------------- Initial Production ------------------
☐ Fall ‘08 – UPS order 50-100 initial production vehicles
☐ Summer ‘09 – Deliver vehicles
Project Overview ...

- **Purpose**
  - To expedite the engineering, manufacture and deployment of the first pre-production full series hydraulic hybrid UPS trucks.
  - 2 to 10 vehicles – depending upon funding
  - Establishes the production basis for several urban HHVs that can directly use this same technology (UDVs, shuttle and school buses).

- **EPA’s Role**
  - A facilitator for UPS to help them procure the initial pre-production fleet of vehicles.
  - Help locate those organizations that are interested in helping to advance the commercialization of the world’s most cost effective hybrids

- **UPS’ Role - expected to be the primary “customer”**
  - The actual ownership relationship (ownership, lease, loan, other…) will be determined by UPS and the OEM/supplier
Potential Funding Assistance Opportunities

1. Pioneering Partner - $500k
   - Get 2-3 trucks deployed in a city of your choosing
   - Get to identify yourself as a Pioneering Partner and place your logo on those trucks

2. Contributing Partner - $100k to $200k
   - Get 1 truck deployed in a city of your choosing
   - Get to identify yourself as a Contributing Partner and place your logo on that truck
Other Funding Assistance Opportunities

If your organization is interested in funding the next big breakthrough in hybrids,

...Consider investing in the demonstration of the world’s first Free-Piston Engine in a series HHV.

- Estimated project cost - $5 million over 2 years
- Unique engine that would significantly improve efficiency and dramatically reduce cost
Other Funding Assistance Opportunities

...Help advance demonstration of ultra-clean and efficient engines for HHVs

- E85/M85 engines
- Gasoline HCCI engines

Estimated project cost - $750k/yr each for 2 years