MOBILE FLUID POWER SYSTEMS
High Level Summaries

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• **Objective:**
  
  o NREL supporting the Vehicle Technologies Office to:
    
    – Develop a high-level understanding of the market size for mobile off-highway fluid power applications
    
    – Define a probable range of energy consumed by the mobile off-highway fluid power market
    
    – Understand the potential impacts of efficiency improvements based on the above
MARKET SHARE – COMPONENT UNIT SALES

- Mobile Off-Highway Hydraulic Fluid Power (67%)
  - Construction
  - Agriculture
  - Material Handling
  - Oil & Gas
  - Mining

- Construction & Ag. accounted for 75% of the mobile off-highway market segment

Light Duty cars and trucks (15.2 quads) (54.5%)

Heavy Duty trucks (5.8 quads) (20.9%)

Off-Road (2.1 quads) (7.6%)

Total Transportation Sector in 2016 = 27.8 quads

1 “Quad” = 1 quadrillion ($10^5$) BTUs = ~ 8 billion gallons of gasoline

Generated from ORNL Transportation Energy Data Book, Edition 35, Table 2.8
MOBILE FLUID POWER - EFFICIENCY

Efficiency

- Engine Efficiency (%)
- Pump Efficiency (%)
- Control System Efficiency (% → Positive Work / Pump Energy)

Controllability

- Machine Efficiency (% → Positive Work / Chemical Energy)

Machine Fuel Efficiency (Tons/liter of fuel)

The engine portion of the system is well understood, and its efficiency is linked to the rest of the fluid power system by demand for power in terms of torque and crank speed. Overall engine efficiency may be on the order of roughly 30-45% with potential improvements of 10-15% where fluid power system improvements may move operation to more efficient speed/load points or reduce engine size.

The remainder of the fluid power system is typically comprised of a pump, valves to throttle pressure and flow, fluid transfer, and hydraulic cylinders / motors. Peak demands often drive design, with the system operating below peak for most of its duty cycle. A very high-level estimate for “average” efficiency of this portion across all types and duty cycles is on the order of 21%\textsuperscript{1} - 30%\textsuperscript{2}.  

\textsuperscript{1} P. Achten, T. Brink, J. Potma, M. Schellekens, and G. Vael, “A Four-Quadrant Hydraulic Transformer for Hybrid Vehicles”, The 11\textsuperscript{th} Scandinavian International Conference on Fluid Power, Sweden, 2009. \textsuperscript{2} 2017 Industry interviews
ENERGY CONSUMPTION – LOWER BOUND ESTIMATE

- NFPA industry data provided for 2012 ORNL tech report:
  - 21% system efficiency
  - OEM provided fuel consumption data
  - Approx. 0.36 quads of energy consumed

Light Duty cars and trucks
(15.2 quads)
(54.5%)

Heavy Duty trucks
(5.8 quads)
(20.9%)

Off-Road
(2.1 quads, 7.7%)

Air
Other
(4.6 quads)
(16.4%)

Total Transportation Sector in 2016 = 27.8 quads
Lower Bounds of Mobile Fluid Power Consumption = 1.3%

*ORNL/TM-2011/14 and Transportation Energy Data Book: Edition 35, Table 2.8
ENERGY CONSUMPTION – UPPER BOUND ESTIMATE

- Off-hwy transportation related fuel consumption from EPA Motor Vehicle Emission Simulator (MOVEs) 2014a model:
  - Construction, agriculture, mining, industrial and logging equipment

<table>
<thead>
<tr>
<th>Off-Highway Transportation-Related Fuel Consumption from the Nonroad Model, 2014 (trillion Btu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agricultural equipment</td>
</tr>
<tr>
<td>Tractors, mowers, combines, balers, and other farm equipment which has utility in its movement.</td>
</tr>
<tr>
<td>Gasoline  Diesel  LPG  CNG  Total</td>
</tr>
<tr>
<td>8.6      599.3  0.0  0.0  607.9</td>
</tr>
<tr>
<td>Airport ground equipment</td>
</tr>
<tr>
<td>Gasoline  Diesel  LPG  CNG  Total</td>
</tr>
<tr>
<td>0.3      16.1   0.3  a    16.7</td>
</tr>
<tr>
<td>Construction and mining equipment</td>
</tr>
<tr>
<td>Pavers, rollers, drill rigs, graders, backhoes, excavators, cranes, mining equipment</td>
</tr>
<tr>
<td>Gasoline  Diesel  LPG  CNG  Total</td>
</tr>
<tr>
<td>11.3     967.6  1.9  a    980.9</td>
</tr>
<tr>
<td>Industrial equipment</td>
</tr>
<tr>
<td>Forklifts, terminal tractors, sweeper/scrubbers</td>
</tr>
<tr>
<td>Gasoline  Diesel  LPG  CNG  Total</td>
</tr>
<tr>
<td>9.0      137.8 207.1 18.8 372.8</td>
</tr>
<tr>
<td>Logging equipment</td>
</tr>
<tr>
<td>Feller/buncher/skidder</td>
</tr>
<tr>
<td>Gasoline  Diesel  LPG  CNG  Total</td>
</tr>
<tr>
<td>1.8      22.4   a    a    24.2</td>
</tr>
<tr>
<td>Railroad maintenance equipment</td>
</tr>
<tr>
<td>Gasoline  Diesel  LPG  CNG  Total</td>
</tr>
<tr>
<td>0.2      3.8   0.0  a    3.9</td>
</tr>
<tr>
<td>Recreational equipment</td>
</tr>
<tr>
<td>Off-road motorcycles, snowmobiles, all-terrain vehicles, golf carts, specialty vehicles</td>
</tr>
<tr>
<td>Gasoline  Diesel  LPG  CNG  Total</td>
</tr>
<tr>
<td>185.7      2.1  0.1  a    187.9</td>
</tr>
<tr>
<td>Total</td>
</tr>
<tr>
<td>Gasoline  Diesel  LPG  CNG  Total</td>
</tr>
<tr>
<td>216.9     1,749.2 209.4 18.8 2,194.3</td>
</tr>
</tbody>
</table>

Source:

- Assuming 95% of fuel was consumed by the fluid power system
- Aprx. 1.9 quads of energy consumed

*NREL analysis and Transportation Energy Data Book: Edition 35, Table 2.8
Annual Savings of Quads Consumer per 1% Efficiency Increase

A 15% efficiency increase yields an annual savings of $2.9B - $15.3B

A 5% efficiency increase yields an annual savings of $1.3B - $7.1B

Improvements from a 21% efficient fluid power system
NREL’s MOBILE FLUID POWER STUDY

• Preliminary Results:
  o Construction and Agriculture dominate the mobile off-highway fluid power market
  o NFPA industry data provided for 2012 ORNL tech report resulted in a lower bound of 0.36 quads of energy consumed/yr:
    – 21% system efficiency
    – OEM provided fuel consumption data
    – Lower boundary of market
  o Fuel consumption from EPA MOVES2014a Model resulted in an upper bound of 1.9 quads of energy consumed/yr
    – Construction, ag., mining, industrial, and logging
    – 95% of fuel consumption applied to fluid power system
    – Upper boundary of market
  o Energy Consumption Range of 0.36 – 1.9 quads per year resulting in $7B-$36.8B per year
  o A 5% efficiency increase produces a potential of $1.3B – $7.1B savings per year
  o A 15% efficiency increase produces a potential of $2.9B - $15.3B savings per year
2017 NFPA TECHNOLOGY ROADMAP

Eric Lanke
President/CEO National Fluid Power Association
2017 NFPA Technology Roadmap
Increasing the Energy Efficiency of Fluid Power Components and Systems
September 12, 2017
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- Sujan Dhar, Simerics
- Cameron MacNeil, Stauff Corporation
- Mike Stewart, Steelhead Composites
- Koichi Tsukane, Sumitomo Heavy Industries
- John Kess, The Toro Company
- Travis Peterson, Walvoil Fluid Power
- Tony Zingman, Wandfluh of America
- Sean McCarthy, World Wide Fittings
- Steve Caver, Yates Industries
Roadmap Elements

- **Customer Driver**: The business or technology objectives of fluid power customers. They serve the needs of their own customers, and are not necessarily connected to their use of fluid power.

- **Research Challenge**: The broad areas of attention that must be addressed if fluid power is to meet or better meet the customer needs described by the drivers.

- **Research Target**: The objectives that quantify or otherwise describe successful pre-competitive strategies for pursuing the research challenges.
Customer Drivers/Research Challenges

**Customer Drivers**
- Increased productivity and performance
- Increased availability/up-time
- Lower total and life cycle costs
- Increased ease/predictability of maintenance
- Quieter machines
- Machines that are compliant with safety regulations

**Research Challenges**
- Increase energy efficiency
- Improve reliability
- Reduce size and weight
- Build “smart” components and systems
- Reduce environmental impact
- Improve energy storage capabilities
- Improve fast and accurate control
Research Targets – Energy Efficiency

• Reduce the energy consumption of fluid power systems, including, but not limited to, efforts to reduce the pressure loss between power source and actuation, efforts to reduce parasitic system losses, and through the use of energy efficient fluids.

• Improve the energy recovery methods of fluid power systems, specifically not their energy storage capabilities, but their ability to recover and immediately reuse energy.

• Reduce the power loss experienced by fluid power components.

• Increase the overall energy conversion efficiency from fuel to useful work through the use of hybridization, better engine management, and increased component integration.
Off-highway Vehicle Efficiency Improvement Presentation

September 12, 2017

Prof Kim A. Stelson
University of Minnesota
Director – Center for Compact & Efficient Fluid Power
Barriers to Efficiency

• Inefficient system architecture
  – Hydraulic work circuits use throttling
  – Systems (hydraulics and engine) operate in inefficient regions during duty cycle
  – Suboptimal mechanical system designs
  – Suboptimal control systems

• Component inefficiencies, including fluids

• Highly variable duty cycles

• Lack of design and modeling tools

• Lack of standard duty cycles for comparison
Target areas for improving energy efficiency

• Focus on wheel loaders and excavators... they consume the most energy
• Efficiently match required pressures to different loads
• Expand the use of energy recovery
  – Energy variations within a duty cycle provide opportunities for recovery. Repeatable cycles are easiest.
• Operate engine and hydraulics within an optimum range over duty cycle
• Optimize machine design for intended application(s)
• Improve design practices (do not oversize components, undersize lines, or use incorrect fluids)
Leading solutions

• New architectures
  – Displacement control, multiple pressure levels, transformers and free piston engine pumps.

• Hybridization
  – Electric, hydraulic, flywheel or combination

• Better components, including fluids

• Better engine management including engine off

• Connectivity

• Heat recovery

• Better tools and education for mechanical, controls and systems design
Purdue Displacement Controlled Architecture

- The world’s first 22-ton displacement controlled (DC) excavator prototype was built at Purdue University in collaboration with an industry partner in 2013.
- Hybridizing work functions provides additional energy savings.
IFAS Aachen STEAM Architecture

- Two pressure system

- Accumulator charging circuit via digital operation of engine/pump (full load or idle)

- Independent metering valve control for all actuators
University of Minnesota Free Piston Engine Pump (FPEP) Architecture

- Opposed Piston Opposed Cylinder (OPOC) Design
- Direct Injection
- Uniflow scavenging
- HCCI combustion

- Variable compression ratio
- Better fuel economy
- Multi-fuel operation
- Higher power density
- Modularity
- Internally balanced

Coils
Back iron
Permanent magnets
Energy Recovery

- Energy recovery enabled by additional power source
- High amount of recoverable negative work
- Drives with high recovery potential
  - Boom
  - Swing
- Boom energy recovery more complex due to low load pressure
# Excavator boom and swing recovery hybrids

<table>
<thead>
<tr>
<th>Provider</th>
<th>Recovery Mode</th>
<th>Storage Technology</th>
<th>Fuel Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Komatsu</td>
<td>Swing</td>
<td>Battery</td>
<td>25%</td>
</tr>
<tr>
<td>Kobelco</td>
<td>Swing</td>
<td>Battery</td>
<td>16%</td>
</tr>
<tr>
<td>Hitachi</td>
<td>Swing</td>
<td>Battery</td>
<td>31%</td>
</tr>
<tr>
<td>Caterpillar</td>
<td>Swing</td>
<td>Accumulator</td>
<td>25%</td>
</tr>
<tr>
<td>Sennebogen</td>
<td>Boom</td>
<td>Accumulator</td>
<td>30%</td>
</tr>
<tr>
<td>Mantsinen</td>
<td>Boom</td>
<td>Accumulator</td>
<td>35%</td>
</tr>
<tr>
<td>Liebherr</td>
<td>Boom</td>
<td>Accumulator</td>
<td>30%</td>
</tr>
<tr>
<td>Ricardo</td>
<td>Boom</td>
<td>Flywheel</td>
<td>10%</td>
</tr>
<tr>
<td>Doosan</td>
<td>Swing /Boom</td>
<td>Accumulator</td>
<td>10%</td>
</tr>
<tr>
<td>Hyundai</td>
<td>Swing /Boom</td>
<td>Accumulator</td>
<td>20%</td>
</tr>
<tr>
<td>Kobelco</td>
<td>Swing /Boom</td>
<td>Accumulator</td>
<td>60%</td>
</tr>
<tr>
<td>Purdue</td>
<td>Swing /Boom</td>
<td>Accumulator</td>
<td>40-50%</td>
</tr>
<tr>
<td>IFAS Aachen</td>
<td>Swing /Boom</td>
<td>Accumulator</td>
<td>30%</td>
</tr>
</tbody>
</table>

*Source: H. Murrenhoff, keynote address, IFCP 2017, Hangzhou, China*
CAT 336E H Hydraulic Hybrid Excavator

The design of the 336E H is relatively straightforward, utilizing three building block technologies to achieve fuel savings.

**CONSERVE FUEL**
The Electronic Standardized Programmable (ESP) pump senses when there's a load on the engine and increases the amount of hydraulic flow needed. It ensures smooth transition between power sources, maximizing efficiency and productivity of the engine and pump. Simply put, it provides power when you need it and reduces it when you don't.

**REUSE ENERGY**
The hydraulic hybrid swing system consists of a pair of nitrogen gas accumulators that absorb energy from the swing and then uses that energy to do work. This recovers otherwise wasted swing braking energy and results in less load on the engine.

**OPTIMIZE PERFORMANCE**
Reflected as the “brains” of the system, the Adaptive Control System (ACS) valve tells the oil where to go precisely when it is needed. The ACS independently controls inflow and outflow restrictions to and from each circuit of the machine to maximize performance with no loss of power.

“No other commercially available technology has higher power density than hydraulics.”

“Up to 25% fuel savings.”

“Extraordinarily quiet, too.”
Improved components

• High speed digital valves, both electronic and mechanical “virtually variable displacement”
• Variable linkage pump
• Independent metering valves
• Better energy storage (lightweight composite accumulator, Ricardo flywheel, strain energy accumulator)
• Better fluids
Digital displacement pump (Artemis)

- Replacement of the original pump with a Digital Displacement® pump is expected to reduced fuel consumption by around 16%.
- The long term development goal is to demonstrate a digital displacement excavator with reduced fuel consumption of ~50%.
High VII hydraulic fluid efficiency gains

- 26-ton Caterpillar crawler excavator in comprehensive tests
- Accurate recording of the saving potential depending on the type of use
- Statistically valid data generated

<table>
<thead>
<tr>
<th></th>
<th>Fuel consumption per cycle</th>
<th>Efficiency increase (buckets per liter of fuel)</th>
<th>Productivity increase (buckets per cycle)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leveling</td>
<td>–</td>
<td>Up to 4%</td>
<td>–</td>
</tr>
<tr>
<td>Drive mode (meters)</td>
<td>–</td>
<td>Up to 11%</td>
<td>Up to 8%</td>
</tr>
<tr>
<td>Digging (at full speed)</td>
<td>Up to 3%</td>
<td>Up to 15%</td>
<td>Up to 15%</td>
</tr>
</tbody>
</table>
Engine Management

- Engine typically operates at high speed
- Additional power source from hybridization required to reduce engine speed
- More efficient operation of engine and pump in sweet point
- Reduce “high idle” fuel rate
- On/Off operation possible with hybridization
Connected and Autonomous Off-Road Vehicles

- Connectivity and automation offer new opportunities for energy savings for off-road vehicles.
- Energy saving can be achieved at three levels: work site level, vehicle level and powertrain level.
- Efficient and safe testing methods are required to evaluate connected vehicle applications.
- Construction and agriculture worksites offer a controlled environment for connected vehicle technology development,
Off-road vehicles standard test procedure(s) and simulation tools

Off-highway vehicles equivalent to EPA driving cycles does not exist.

Off-highway vehicles modeling environment equivalent to Autonomie does not exist.