WELCOME TO NREL!!
7:45 am – 8:15 am

Please be sure to sign in with security and display your badge throughout the duration of your visit.

For those of you joining via teleconference, please be sure to mute your phone until actively participating in the discussion.
NREL WELCOME

Dr. Chris Gearhart
Director, Transportation and Hydrogen Systems Center
at a Glance

1,700 Employees, plus more than 400 early-career researchers and visiting scientists

World-class facilities, renowned technology experts

Partnerships with industry, academia, and government

Campus operates as a living laboratory

National economic impact $872M annually
NREL advances the science and engineering of energy efficiency, sustainable transportation, and renewable power technologies and provides the knowledge to integrate and optimize energy systems.
NREL’s Science Drives Innovation

Renewable Power
- Solar
- Wind
- Water
- Geothermal

Sustainable Transportation
- Bioenergy
- Vehicle Technologies
- Hydrogen

Energy Efficiency
- Buildings
- Advanced Manufacturing
- Government Energy Management

Energy Systems Integration
- High-Performance Computing
- Data and Visualizations
Sustainable Transportation
The laboratory contributed to first-of-a-kind commercialization of cellulosic ethanol technologies in the United States.

**Market Impact**

- Supported **78% reduction** in the cost of converting biomass into cellulosic ethanol
- Integrated and scaled up bioconversion technology
- Contributed to **DuPont and POET cellulosic ethanol biorefineries**
- Modeled cost-competitive production of cellulosic ethanol
Key Research Areas

- **Using refinery infrastructure that already exists** – feasibility of co-processing pyrolysis oil (drop-in hydrocarbons) with Ensyn Corporation

- **Producing natural bioplastics, acids, and alkanes** – pathway found in nature (lignin valorization) uses “waste” lignin

- **Developing new chemicals and materials** – includes renewable carbon fiber, sustainable ammonia production, ethylene via sunlight, bioconversion of methane to lactate
R&D breakthroughs provide **efficient, high-performance, and market-ready transportation solutions** for consumers and industry.

**Market Impact**

- Per capita consumer fuel economy savings of **$600/year**
- Getting new technologies into the hands of consumers to save over **2B gallons** of conventional fuel per year
- Electric vehicle battery cost **70% less than 2008**
- Fuel efficiency standards with potential for **$170 billion** cost savings for commercial truck operators
- Fuel cell electric vehicle range of more than **300 miles**
Path to Sustainable Transportation Technologies

Key Research Areas

• **Co-optimizing fuels and engines** – R&D to maximize performance, efficiency, and compatibility with existing infrastructure

• **Increasing sustainable mobility** – connected and autonomous transportation innovations for intelligent, efficient, integrated network

• **Reducing expense of battery development** – Computer-Aided Engineering for Electric-Drive Vehicle Batteries (CAEBAT) tool

• **Improving efficiency of heavy-duty vehicles** – commercial truck fuel, engine, thermal management, and powertrain innovation

• **Demonstrating electrification of vehicles** – energy storage for plug-in electric and fuel cell electric vehicles; power electronics; and infrastructure data collection, sharing and analysis to boost accessibility, performance and utilization
NREL’s world-class research and cutting-edge innovations:

Create American jobs
Boost U.S. economic growth
Strengthen our energy security
Thank You

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

NREL.gov
ATTENDEE
INTRODUCTIONS
Lauren Lynch, NREL

• Please Tell Us:
  — Your name
  — Company/Academic institution
  — Role relating to mobile fluid power

• Please fill out your name on the table tent

56 Registrations as of Sept 11

Trade Groups and Lobbying = 2
OEMs = 4
National Labs + DOE = 13
Universities (inc. CCEFP) = 23
Tier 1s and Integrators = 23
WELCOME FROM DOE

Gurpreet Singh
Program Manager, Vehicle Technologies Office DOE
BACKGROUND & KICKOFF

Dr. Michael Weismiller
Vehicle Technologies Office, DOE
Energy Efficient Fluid-Power Systems for Off-Road Vehicles
Research Needs Workshop
Mike Weismiller
Kevin Stork
Gurpreet Singh
Department of Energy, Vehicle Technologies Office
September 12, 2017
The Vehicle Technologies Office (VTO) aims to:

- increase domestic energy **security**
- reduce operating **cost** for consumers & businesses
- improve global **competitiveness** of US Industries

*By supporting R&D in...*

- **Fuel Diversification**
  - Domestic, Diverse, Alternative, Clean Fuels
- **Vehicle Efficiency**
  - Energy Efficient Vehicle Technologies
- **Mobility Systems**
  - Energy Efficient Transport Systems
Vehicle Technology Office - Approach

Portfolio Approach

Public / Private Partnerships

Target Driven With Ambitious Goals

Fuel Economy (LDV) +50%
Weight - 25%
55% Heavy Duty Truck BTE
Costs: Battery = ICE

Academia and Intergovernmental

Battery = ICE
Current State of U.S. Energy Flow

Estimated U.S. Energy Consumption in 2016: 97.3 Quads

Source: LLNL, March 2017. Data is based on EIA/EIA MER (2016). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. This chart was revised in 2017 to reflect changes made in mid-2016 to the Energy Information Administration’s analysis methodology and reporting. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 45% for the residential sector, 65% for the commercial sector, 71% for the transportation sector, and 49% for the industrial sector which was updated in 2017 to reflect DOE’s analysis of manufacturing. Totals may not equal sum of components due to independent rounding. LLNL-M1-615017
Energy Use of Fluid-Power Systems

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%)

Air

Other (4.6 quads) (16.4%)

Marine

Rail

Pipeline

Total Transportation Sector in 2016 = 27.8 quads

Generated from ORNL Transportation Energy Data Book, Edition 35, Table 2.8
Energy Use by Fluid Power

“...mobile hydraulic systems use 0.36-1.26 quads of energy.”

NREL workshop team has updated study.
Legislative and Policy Drivers

FY17 Energy and Water Development and Related Agencies Appropriations Conference Report:

Within available funds for Fuel and Lubricant Technologies, the agreement provides up to $5,000,000 to support improving the energy efficiency of fluid power systems for commercial off-road vehicles.

FY18 HEWD Mark-up Report:

The Committee notes that the commercial off-road vehicle sector, including industrial, mining, and farm equipment, consumes over two quads of energy per year. The Department is encouraged to consider activities that promote technologies to reduce the energy consumption of commercial off-road vehicles and provides up to $10,000,000 to support this effort.

FY18 SEWD Report:

The Committee recognizes that the commercial off-road vehicle sector, including industrial, mining, and farm equipment, consumes over 2 Quads of energy per year and directs the Department to continue activities to reduce the energy consumption of commercial off-road vehicles. The Committee recommends $5,000,000 to continue improving the energy efficiency of fluid power systems for commercial off-road vehicles.
Legislative and Policy Drivers

Administration Guidance

OMB Memo on Research and Development Priorities, 2/5 are relevant

“American Energy Dominance -

... Agencies should invest in **early-stage**, innovative technologies that show promise in harnessing American energy resources safely and efficiently. Federally-funded energy R&D should continue to reflect an *increased reliance on the private sector to fund later-stage research, development, and commercialization of energy technologies.*

“American Prosperity -

Federal investment in R&D plays an important supporting role in America’s economic growth. Properly executed, it can lead to tremendous job creation in new businesses and industries.... *Working in tandem, the Government and the private sector can promote the nation’s economic growth* through innovation, and create new products and services for the American people. “
Workshop Objectives

What are we looking for today?
• Ideas that can lead to projects that will advance the science base underlying increased efficiency in off-road vehicles.
• Specific focus on fluid power, but other needs of off-road vehicles are welcome.

What are we not looking for today?
• Product development
• Deployment activities

How do we plan to execute this activity?
• Multiple projects, balancing competitively-awarded, cost-shared cooperative agreements and projects at DOE National Labs
Thank You

Mike Weismiller
michael.Weismiller@ee.doe.gov

Kevin Stork
Kevin.stork@ee.doe.gov

Gurpreet Singh
Gurpreet.singh@ee.doe.gov

https://energy.gov/eere/vehicles/vehicle-technologies-office
MOBILE FLUID POWER SYSTEMS
High Level Summaries

Lauren Lynch, NREL
Brad Zigler, NREL
Eric Lanke, NFPA
Kim Stelson, CCEFP/U. of Minnesota
Mobile Fluid Power - High Level Analysis

Market Share
Energy Consumption
Potential Efficiency Increases/Savings

Lauren Lynch, Brad Zigler

September 12, 2017

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.
Objective:

- 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

TRANSPORTATION SECTOR ENERGY CONSUMPTION

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

Total Transportation Sector in 2016 = 27.8 quads

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

Heavy Duty trucks
(5.8 quads)
(20.9%)

Off-Road
(2.1 quads)
(7.6%)

Air

Other
(4.6 quads)
(16.4%)

Pipeline

Marine

Rail

Generated from ORNL Transportation Energy Data Book, Edition 35, Table 2.8
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%\(^1\) - 30%\(^2\).


\(^2\) 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

![Energy Consumption Diagram]

- 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-Highway Transportation-Related Fuel Consumption from the Nonroad Model, 2014**

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

Source:

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

- 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*
• 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 results in $7B- $36.8B per year
2017 NFPA Technology Roadmap
Increasing the Energy Efficiency of Fluid Power Components and Systems
September 12, 2017
NFPA Roadmap Committee

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Vice Chair
• Mark Bokorney, Sun Hydraulics

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• Frank Latino, Festo Corporation
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• Scott Paxton, Lehigh Fluid Power

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• Sujan Dhar, Simerics
• Cameron MacNeil, Stauff Corporation
• Mike Stewart, Steelhead Composites
• Koichiro 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
**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.
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
• 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
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
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

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

“Up to 25% fuel savings.”

“Extraordinarily quiet, too.”

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**

Referred to 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.
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.
BREAK
10:00 am – 10:15 am
Margo Melendez, NREL

- Objective of presentations w/open dialogue
- Pre-competitive, early stage areas of research opportunities focus
- Low Technology Readiness Levels
- Each facilitated discussion session will begin with an opening intro presentation either directly related to the discussion topics, or a higher level intro to initiate discussion
• Ranges from 1–10 (from basic science to product ready for the market)
• “Low-TRL” = TRL 1–3
• The word “engineering” first shows up in the definition of TRL 6.
• TRL 1 = Basic principles observed and reported.
• TRL 2 = Technology concept and/or concept formulated. Moves the idea from pure to applied research.
• TRL 3 = Analytical and experimental critical function and/or characteristic proof of concept
• TRL 4 = Component and/or system validation in laboratory environment. First step in determining whether the individual components will work together as system.
Focused Application, Data Needs, Standardized Testing etc.

Lonnie Love, ORNL
Ken Kelly, NREL
Brad Zigler, NREL
Fluid Power R&D Opportunities

Lonnie Love, Ph.D.
Corporate Fellow
Oak Ridge National Laboratory
2010 DOE/ORNL/NFPA Energy Study

- Fluid power is defined as the application of pumped or compressed fluid (liquid or gas) to provide force and motion to mechanisms.

- In 2010, DOE ITP contracted ORNL to conduct a fluid power study.
  - Objective was to establish a ballpark estimate on **market size, energy consumed, emissions generated and existing efficiency levels**.
  - ORNL teamed with NFPA and 31 industrial partners spanning all major application areas.
  - Industrial partners provided proprietary data on systems, energy consumption, duty cycles and efficiencies.
Results of Study

- Segmented industry into 4 areas
  - Mobile hydraulics, industrial hydraulics, pneumatics and aerospace

- Results
  - Industry is a huge manufacturer as well as supporter of manufacturing
    - $17.7B in component sales, > $226B in systems sales
  - 2 to 3 Quads of energy is consumed driving fluid powered systems
    - **Mobile hydraulics between 0.4 and 1.3 Quads/yr**
    - Industrial hydraulics 1.1 Quads/yr
    - Pneumatics 0.5 Quads/yr
    - Aerospace 0.02 Quads/yr
  - Average efficiency is under 22%

Opportunities for high profile industry wide demonstrations

- CONEXPO/AGG
  - Massive consolidation of fluid power industry every 3 years
  - 120,000 world-wide attendees
  - Target high level of emerging technologies through demonstrations
Private/Public Example: Project AME
“Additive Manufacturing Excavator”

Project AME consists of three demonstrations of additive manufacturing in one large-scale application
1. The heat exchanger will be printed using the Concept Laser
2. The cab will be printed on the Big Area Additive Manufacturing system out of polymer composite material
3. The stick, a large hydraulically articulated arm, will be printed on the Wolf Robotics metal system

Project included CNH, NFPA, CCEFP, Lincoln Electric, Cincinnati Inc...
METHODOLOGIES FROM DUTY CYCLE
DNA COLLECTION & ANALYSIS

Ken Kelly
Team Leader – Commercial Vehicle Technologies, NREL
Focused Applications
Duty Cycle

Ken Kelly
Team Leader – Commercial Vehicle Technologies

Fluid Power Systems Workshop
September 12, 2017
**Kinetic Intensity** is a measure of drive cycle kinetics to define how much ‘*stop and go*’ is in the cycle

- Derived from the ratio of aerodynamic speed and characteristic acceleration
- **Characteristic acceleration**: Measures the inertial work to accelerate and/or raise the vehicle per unit mass per unit distance over the cycle.
- **Aerodynamic speed**: Measures the ratio of the overall average cubic speed to the average speed

Duty Cycle Characterization and Evaluation Towards Heavy Hybrid Vehicle Applications

Importance of Duty Cycle for Commercial Vehicles

More Regen Potential

Increased Energy Storage Required
Understanding Modes of Operation

Characteristic Acceleration vs Aerodynamic Speed

- Cluster 1: $K_i = 25 \frac{ft}{mi}
- Cluster 2: $K_i = 7.5 \frac{ft}{mi}
- Cluster 3: $K_i = 5 \frac{ft}{mi}
- Cluster 4: $K_i = 0.33 \frac{ft}{mi}$

Maximum Speed vs Average Driving Speed

- Cluster 1: HHDDT Creep, HHDDT Transient, UDDS-HD, Creep/Queue, Port/Near Dock, Local
- Cluster 2: HHDDT Cruise
- Cluster 3: Metro Highway Cruise
- Cluster 4: Metro Highway Drive Cycle
Engine-based Drive Cycles

Vehicle-Based Duty Cycle Metrics
- Aerodynamic Speed (ft/s)
- Characteristic Acceleration (ft/s²)
- Percent (%) of total cycle distance below 55 mph
- Percent (%) of total cycle duration at 0 mph
- Number of stops per mile
- Mean (nonzero) driving speed (mph)
- Maximum driving speed (mph)
- Standard Deviation of nonzero driving speed (mph)

Example Engine-based Cycle Metrics:
- average engine load
- maximum engine load
- median load
- standard deviation of engine load
- number of engine loading events per mile traveled (or hour of operation)
- loading ratio (ratio of increasing to decreasing loading rate time)
Idle & PTO Operations

1) Distribution of Engine RPM

2) Distribution of Engine RPM with vehicle speed = 0 (idle + PTO)

3) Time Spent – Driving / Idle / PTO

4) Fuel Consumption
Commercial Vehicle Electrification

Duty Cycle Statistics:

<table>
<thead>
<tr>
<th>Category</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driving Days</td>
<td>17,447</td>
</tr>
<tr>
<td>Kinetic Intensity (1/mi)</td>
<td>3.85</td>
</tr>
<tr>
<td>Stops per mile</td>
<td>5.85</td>
</tr>
<tr>
<td>Avg Acceleration (ft/s²)</td>
<td>0.52</td>
</tr>
<tr>
<td>Average Speed (mph)</td>
<td>15.6</td>
</tr>
</tbody>
</table>

Motor Continuous Rating: 55 kW
Applying Drive Cycle Data – NREL DriveCAT

Objectives:

• Provide a common, publically available, easy to use site for standard and custom drive cycles for medium- and heavy-duty vehicles

• Capture, quantify and compare drive cycle variation across the spectrum of medium- and heavy-duty vocations

• Allows users to download raw time series data of drive cycles for their own use

www.nrel.gov/transportation/drive-cycle-tool
NREL Medium and Heavy-Duty Commercial Vehicle Technologies

For more information:
Kenneth Kelly
National Renewable Energy Laboratory
kenneth.kelly@nrel.gov
phone: 303.275.4465

- NREL Fleet Evaluations Website
  http://www.nrel.gov/transportation/fleettest.html
- Fleet DNA Website
  www.nrel.gov/fleetdna
- DriveCAT
  www.nrel.gov/transportation/drive-cycle-tool
- Publications Available at:
  http://www.nrel.gov/transportation/fleettest_publications.html
DISCUSSION 1

• Opportunities in Market Segments
  o Construction
    – Excavators
    – Skid-Steer
    – Compact Track Loader
    – Dozer
    – Wheel Loader
  o Agriculture
    – Tractor
    – Combine/Forage Harvester
  o Material Handling
  o Oil & Gas
  o Mining

• Pre-Competitive Development Needs

• Pre-Competitive Research Needs
  o Energy Consumption Study
  o Baseline System Efficiency
  o Common Duty Cycle(s)
  o Bench Testing
  o Real World Application Testing

• Standardized testing
• Etc.
LUNCH
11:30 – 12:30
New Architecture Development & Market Barriers, New Technology Development, Hybridization, Market Barriers, etc.

INDUSTRY PERSPEJECTIVE
INDUSTRY PERSPECTIVE

Gary Kassen
Engineering Director, Case New Holland
CNH Industrial Strategy and Fluid Power Needs

Gary Kassen, Engineering Director – Hydraulics/Pneumatics

Golden, CO

September 12, 2017
CNH Industrial – 2016 Sales $23.7 B

- 55% Off-Highway

Trucks

Buses and Coaches

Firefighting Equipment

Civil Protection and Defense Vehicles

Skid SteerLoaders

Crawler Excavators

Engines and Transmissions

Tractors

Combines
CNH INDUSTRIAL: A FIVE-TIME LEADER IN DOW JONES SUSTAINABILITY INDICES

<table>
<thead>
<tr>
<th>Year</th>
<th>CNH Industrial Score</th>
<th>Industry Average Score</th>
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</thead>
<tbody>
<tr>
<td>2011</td>
<td>81</td>
<td>49</td>
</tr>
<tr>
<td>2012</td>
<td>85</td>
<td>51</td>
</tr>
<tr>
<td>2013</td>
<td>88</td>
<td>49</td>
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<td>2014</td>
<td>87</td>
<td>50</td>
</tr>
<tr>
<td>2015</td>
<td>91</td>
<td>52</td>
</tr>
<tr>
<td>2016</td>
<td>90</td>
<td>52</td>
</tr>
</tbody>
</table>
Megatrends & Related Material Topics

Climate Change

Renewable Energy

Water and Waste Efficiency

Local Community Engagement

Circular Product Lifecycle

Trade, Regulations and Public Debate

CO₂ and Other Air Emissions

Autonomous Vehicles

Value Chain Management

Innovation-to-Zero

Employee Engagement

Self-Sustaining System for Food

Food Scarcity & Food Security

Digital Workplaces

Innovative and digital world

Material Topics relevant to Fluid Power

Source: CNH Industrial Sustainability Report, 2016

06 September 2017
Innovation to Zero

- Defects - less warranty/service
- Leaks – No one quality problem with hydraulics
- Waste – Hydraulic oils (longer service life)
- Environmental Impact - Economical environmentally friendly fluids
CO2 & Other Air Emissions

- CO2 (Efficiency)
  - Limit or reduce system losses
  - Variable displacement pumps for cooling & lubrication circuits - provide flow on demand to these circuits
  - Lower engine speeds during roading or lower power operation (use larger displacements to maintain productivity)
  - Independent metering to reduce throttling losses.
  - Flatter oil viscosity curves

- Other Emissions
  - CNG
  - LP
  - Hydrogen

Fluid Power Challenge: Reduce space and higher efficiency to reach equivalent operating time
Methane Power Tractor

PERFORMANCE – TIER 4A T6.175 VS T6 METHANE POWER

<table>
<thead>
<tr>
<th>FEATURES</th>
<th>T6.175 TIER 4A</th>
<th>T6 METHANE POWER</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAX POWER (kW)</td>
<td>129 @ 1800 RPM</td>
<td>132 @ 1800 RPM</td>
</tr>
<tr>
<td>MAX TORQUE (Nm)</td>
<td>726 @ 1500 RPM</td>
<td>740 @ 1500 RPM</td>
</tr>
</tbody>
</table>

Methane Tractor debut at 2017 Farm Progress Show
Methane Advantages

- CO₂ [g/kWh]:
  - Cursor 9 diesel: 800 g/kWh
  - Cursor 9 NG: 700 g/kWh (-14%)
  - Euro VI limits: 600 g/kWh
  - Cursor 9 diesel: 600 g/kWh
  - Cursor 9 NG: 500 g/kWh (-99%)

- PM [mg/kWh]:
  - Euro VI limits: 10 mg/kWh
  - Cursor 9 diesel: 10 mg/kWh
  - Cursor 9 NG: 0.1 mg/kWh (-99%)

- NOₓ [g/kWh]:
  - Euro VI limits: 0.6 g/kWh
  - Cursor 9 diesel: 0.6 g/kWh
  - Cursor 9 NG: 0.3 g/kWh (-50%)

Natural gas (fossil)
CO₂ - 14%

Bio-methane
CO₂ - 100%

06 September 2017
ATS – Diesel Vs. CNG/LPG solution

- **ATS solution is simpler for CNG/LPG engines compared to diesel** not requiring any SCR with related components (DEF tank, pipes and dosing module), **resulting in ~90% smaller volume** (ref. Tier4B)
- Key Challenge is the extremely high exhaust gas temperatures of gas engines when compared with current diesel technology – 750/800 °C Vs. 550 °C
Total Cost of Ownership – Commercial filling station Methane

Not considering urea usage (2% saving) and the elimination of potential fuel theft, the Methane tractor could achieve more than €5500 per year savings compared to a diesel powered tractor.
Total Cost of Ownership – Energy Independent Farm Methane

---

**Fuel Price**

- Diesel: From 1.2 to 1.4 €/kg
- Bio Methane: From 0.7 to 0.8 €/kg

**Energy Value (MJ per kg)**

- Diesel: 44
- Bio Methane: 48

**Engine Efficiency**

- Diesel: 100
- Bio Methane: 83

---

Fuel cost (€/hrs) – Contractors operators (VAT excluded)

- Diesel: 24
- Bio Methane: 16

---

Not considering urea usage (2% saving) and the elimination of potential fuel theft, the Methane tractor could achieve more than €13,000 per year savings compared to a diesel powered tractor.
New Holland T6 LP Powered Tractor

**Similar Benefits to Methane**
- Reduced operating cost 20%-40%
- Less daily maintenance
- No fuel leak soil contamination
- Significant reduction in in-cab and drive-by noise
- 80+ percent reduction in smog-producing hydrocarbon emissions compared with Tier IV diesel
- 90% space reduction for after treatment volume

**Additional Benefits to LP**
- Low pressure fuel tanks
- Wide availability in the US – 70% comes from domestic natural gas
Hydrogen Fuel Cell – New Holland T6

- Splits hydrogen gas (H2) molecule to produce electricity
- Zero emissions
- Lower noise
- High efficiency (150% of diesel)
- Fuel cells are currently expensive but cost could drop dramatically if widely used in automotive
- Limited distribution infrastructure (H2) but could be produced locally on farms
- Requires tanks for pressurized hydrogen fuel (790 bar currently being used in automotive)
Autonomous Vehicles

CNH interpretation of the SAE levels of autonomy

Level 1
Guidance
*All manned vehicles

Level 2
Coordination & Optimization
*All manned vehicles

Level 3
Operator Assisted Autonomy
*Manned back-up

Level 4
Supervised Autonomy
*In-field supervision of unmanned vehicles

Level 5
Full Autonomy
*No local supervision (remote supervision or artificial intelligence)

Available Today → In Development
E-Braking Requirements

Autonomous Vehicles

- Traction Control
- Hill holding / hill start aid
- Brake steering
- Trailer braking (hydraulic and pneumatic)
- ABS
- Auto braking (remote and autonomous - fail operational)
E-Steering Requirements

Autonomous Vehicles

- Steering wheel and joystick capable
- Remote/autonomous function: Fail Operational
## Fluid Power Challenges

### Summary

<table>
<thead>
<tr>
<th><strong>Driver</strong></th>
<th><strong>Fluid Power Need</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Innovation to Zero</td>
<td>Higher reliability</td>
</tr>
<tr>
<td>CO2 &amp; Other Air Emissions</td>
<td>Few leaks</td>
</tr>
<tr>
<td>Autonomous Vehicles</td>
<td>Longer oil life</td>
</tr>
<tr>
<td></td>
<td>Higher efficiencies</td>
</tr>
<tr>
<td></td>
<td>Reduce parasitic losses</td>
</tr>
<tr>
<td></td>
<td>Alternate power sources</td>
</tr>
<tr>
<td></td>
<td>Higher safety level</td>
</tr>
<tr>
<td></td>
<td>Full EH capability</td>
</tr>
</tbody>
</table>
Topic 1 – High Performance Hydraulic fluids

What are the potential system efficiency gains utilizing hydraulic fluids that far exceed specifications defined in current standards:

- ISO 11158 HV
- DIN 51524-3
- ASTM D6158 HVHP
High Performance Hydraulic fluids

In addition to performance criteria for ISO VG 46:

- Inherent Viscosity Index ≤ 130
- Dynamic viscosity @ -40°C ≥ 10,000 cP
- Shear ≥ 15% with 20hr KRL @ 60°C per ISO 26422
- ASTM D943 ≤ 7000 hrs
- Anti-wear depletion ≤ 4000 hrs
Project Outcome

Deliverables at close of project:

- Further technical data (other than OEM) to demonstrate all fluids are NOT the same
- Standardized test methods for comparing efficiency gains at the component and machine level
- Promote development of higher performing fluids within fluid blend companies on a wider scale
DISCUSSION 2 – PRE-COMPETITIVE RESEARCH

• New Architecture Development
  o Fundamental research needs
  o Market barriers
    – Customer acceptance
    – Reliability
    – Durability

• New Technology Barriers
  o Engine efficiency
  o Multi-modal systems
  o Control strategies

• Hybridization
  o Power storage
  o Power density
  o New material
  o Engine efficiency
HYDRAULIC FLUIDS, COMPONENT MATERIAL, TRIBOLOGY

Lelia Cosimbescu, PNNL
George Fenske, ANL
Jun Qu, ORNL
FLUID POWER SYSTEMS:
FLUIDS/MATERIALS – PERFORMANCE/RELIABILITY NEXUS

GEORGE FENSKE
Argonne National Laboratory

JUN QU
Oak Ridge national Laboratory

LELIA COSIMBESCUC
Pacific Northwest National Laboratory

Mobile Fluid Power Workshop
September 12th, 2017
NREL, Denver, CO
FLUID POWER RESEARCH CHALLENGES

Recent NFPA technology roadmap identified key research challenges for fluid power – Many challenges involve issues related to fluid and material properties

- Increasing the **energy efficiency** of fluid power components and systems.
- Improving the **reliability** of fluid power components and systems (e.g., increasing up-time, reducing maintenance requirements, making fluid power safe and easy to use).
- Reducing the **size and weight** of fluid power components and systems while maintaining or increasing their power output.
- Building “smart” fluid power components and systems (i.e., ones that perform self-diagnostics and troubleshooting and integrate easily with “plug and play” functionality).
- Reducing the **environmental impact** of fluid power components and systems (e.g., lowering noise, eliminating leaks).
- Improving and applying the energy storage capabilities of fluid power components and systems.
- Improving and widening the scope of application for **fast, accurate, and cost-effective fluid power control**.

SIGNIFICANT LOSSES (VISCOUS, BOUNDARY, AND LEAKAGE) DUE TO FLOW OF FLUIDS THROUGH THE COMPONENTS AFFECT EFFICIENCY

The rheological and tribological properties of fluids and materials significantly impact overall efficiency, reliability/durability of fluid power components.

“Go with the flow in selecting the right fluid”, Bill Dimitrakis and Rob Profilet, Lubrizol Corp.

Mechanical power at point of use
ENERGY EFFICIENCY INVOLVES MORE THAN MECHANICAL AND VOLUMETRIC EFFICIENCY

Optimizing FP system performance is dependent on many factors including system design, duty cycle, and fluid/material properties.
CHALLENGES/BARRIERS - FLUIDS

Fluid rheology and chemistry

- Understanding of impact of viscosity, which is not independent of temperature, pressure, shear.
  - Effect of viscosity modifier molecular structure on shear stability
  - Viscosity-Pressure relationship, which is less known but significantly impacts the system efficiency

- Understanding complex interactions between additives, basefluids, and surfaces
  - Boundary wear protection by extreme pressure and antiwear setting the floor of the fluid viscosity
  - Compatibility between fluid additive chemistry, e.g., extreme pressure, antiwear, and friction modifier, and the contact surface compositions
  - Impact of system variables – temperature, pressure, mechanical loading, ....
Hydraulic power system performance depends not only on bulk fluid properties such as viscosity, bulk modulus, thermal conductivity, etc., but, also on chemical interactions that occur and fluid material interfaces. Understanding the mechanisms involved in the formation of protective tribochemical films is critical to design/formulate fluids and materials for durable, reliable, sustainable energy-efficient fluid power systems.

- How additives, basefluids, and surfaces interact.

Traditional materials used in hydraulic fluid systems may not be sufficient to achieve energy-efficiency goals. High performance materials, coatings, engineered surfaces required to accommodate more aggressive tribological environment (low viscosity, downsizing, longer ODIs,.....)

Others....

- Standardization of test protocols, robust protocols, duty cycles...
WHAT ARE YOUR THOUGHTS ON CRITICAL CHALLENGES AND BARRIERS?
UNDERSTANDING SURFACE AND LUBRICANT INTERACTIONS

1. Innovative LabScale Testing – Engine Correlations
2. Structure and Chemistry of Protective Tribochemical Films
3. Mechanistic Models of Lubrication
4. Coating-Lubricant Interactions
5. Oil Aging and Degradation

Bench Marking Technologies

<table>
<thead>
<tr>
<th>Coefficient of Friction</th>
<th>E1</th>
<th>E2</th>
<th>E3</th>
<th>E4</th>
<th>E5</th>
<th>G1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.129</td>
<td>0.081</td>
<td>0.165</td>
<td>0.083</td>
<td>0.092</td>
<td>0.085</td>
</tr>
</tbody>
</table>
1. Lubricant Basefluid Development
   - Multifunctional basefluids
   - Hybrid ultra-low-viscosity base fluids

2. Additive Development
   - High performance anti-wear additives
   - Multi-functional viscosity modifiers
   - Multi-functional colloidal additives

3. Materials and Coatings
   - Low friction, wear-resistant coatings
   - Ultra-fast chemical surface treatments
DISCUSSION 3 – FLUIDS & COMPONENT MATERIALS

• Fluids
  o New chemistry
  o Tribology
  o Test standardization
  o Regulation

• Component
  o Electrify
  o Manufacturing improvements
  o Material

• System Optimization
  o Component/fluid development
  o Surface texturing
  o Material

• Integration
  o Modularity
  o Scalability
  o Advanced controls
BREAK
3:00 – 3:15
WRAP-UP & DISCUSSION
NREL, DOE

• Summary
• Round Table
• Next Steps

THANK YOU FOR YOUR PARTICIPATION
SEPTEMBER 13th, NREL CAMPUS TOUR

- 8:30am – 8:45am
  - Margo Melendez – Welcome and Overview (15 minutes) – **ESIF B308**
- 8:45am – 9:30am
  - Ken Kelly (**ESIF B308**) – Fleet DNA and other NREL capabilities (45 minutes)
- 9:30am – 9:45am – 3D simulation demo – **ESIF B311** (15 minutes)
  - SCIENTIST CONFERMED TO DEMO
- 9:45am to 10:45am – (60 minutes) - ESIF (**Energy Systems Integration Facility**) tour
  - Guide: Andrew Hudgins
- 10:45am-10:55am (10 minutes)
  - Break
- 10:55am
  - Buses Depart for TTF
- 11am to 12pm (30-45 minutes) - TTF (**Thermal Test Facility**) Tour
  - Guide: Dr. Ying Shi (**Ying.Shi@nrel.gov**)
- 12pm to 12:45pm (30-45 minutes) – IBRF (**Integrated Biorefinery Research Facility**) Tour
  - Guides: Cindy Gerk/Jim McMillan
- 1pm Conclusion