MOBILE FLUID POWER SYSTEMS
High Level Summaries

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NREL
NATIONAL RENEWABLE ENERGY LABORATORY
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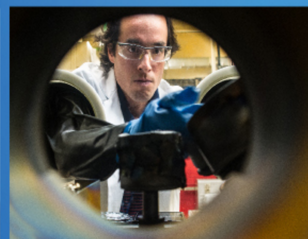
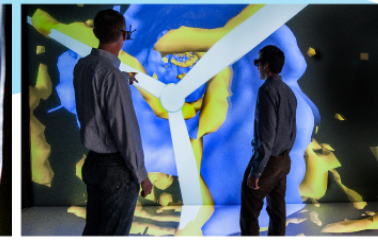
1977 - 2017

Mobile Fluid Power - High Level Analysis

Market Share
Energy Consumption
Potential Efficiency Increases/Savings

Lauren Lynch, Brad Zigler

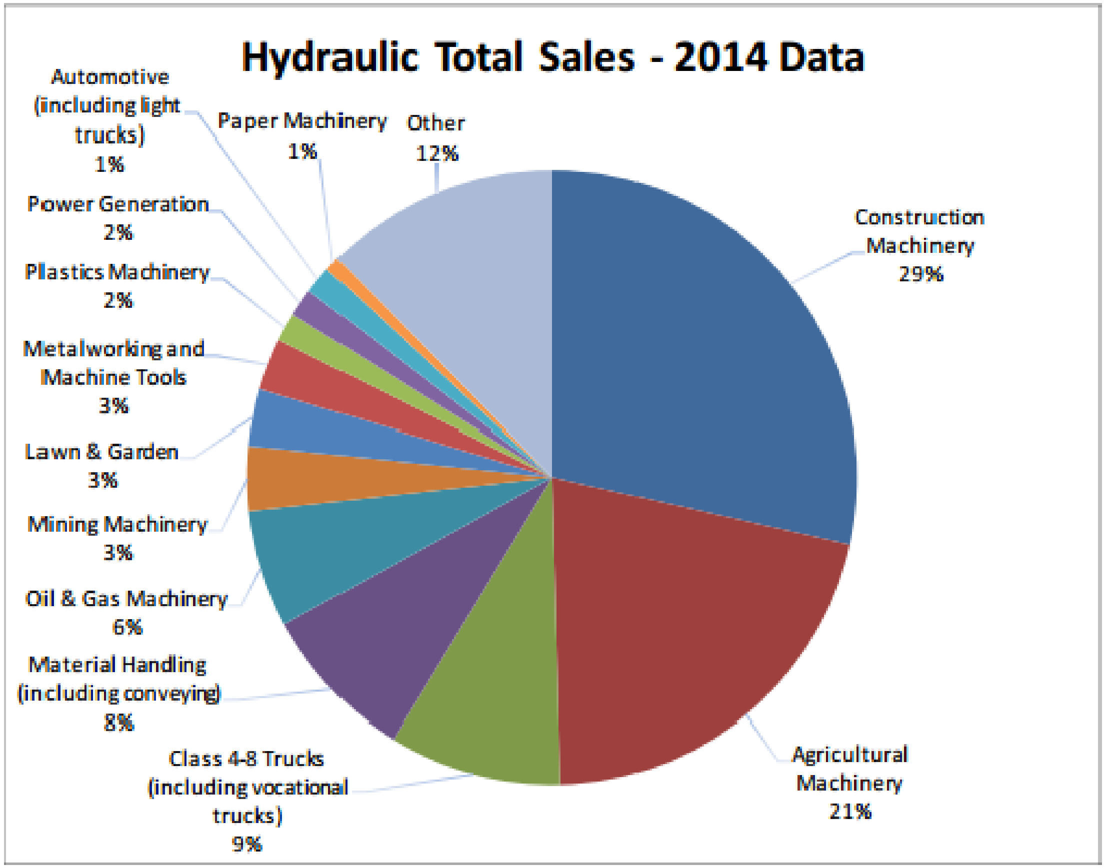
September 12, 2017

NREL's MOBILE FLUID POWER STUDY

- **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

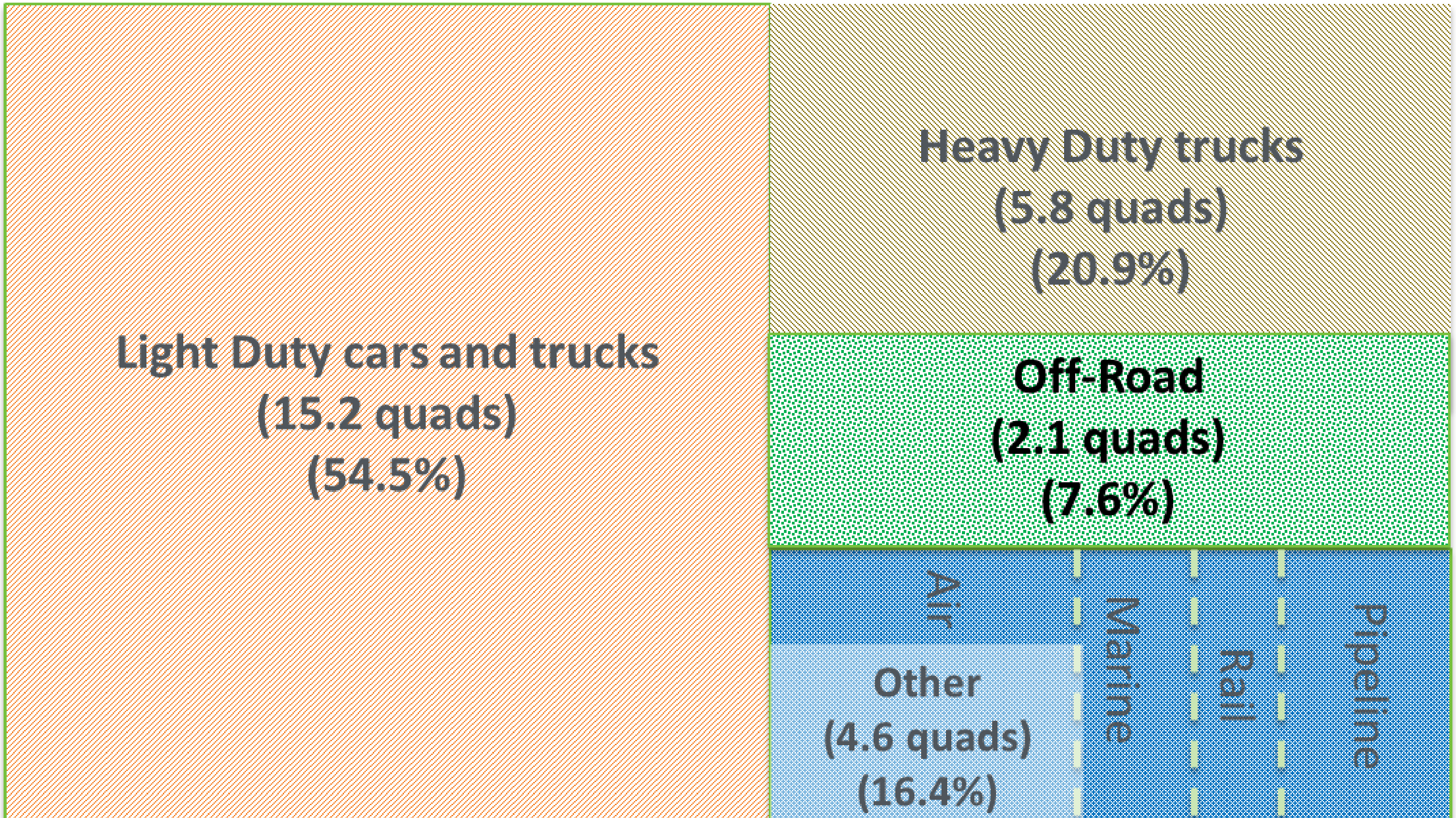


National Fluid Power Association. (Accessed 2017). *2015 Annual Report on the U.S. Fluid Power Industry.* NFPA.

MOBILE FLUID POWER DIVERSITY

MOBILE FLUID POWER DIVERSITY

TRANSPORTATION SECTOR ENERGY CONSUMPTION

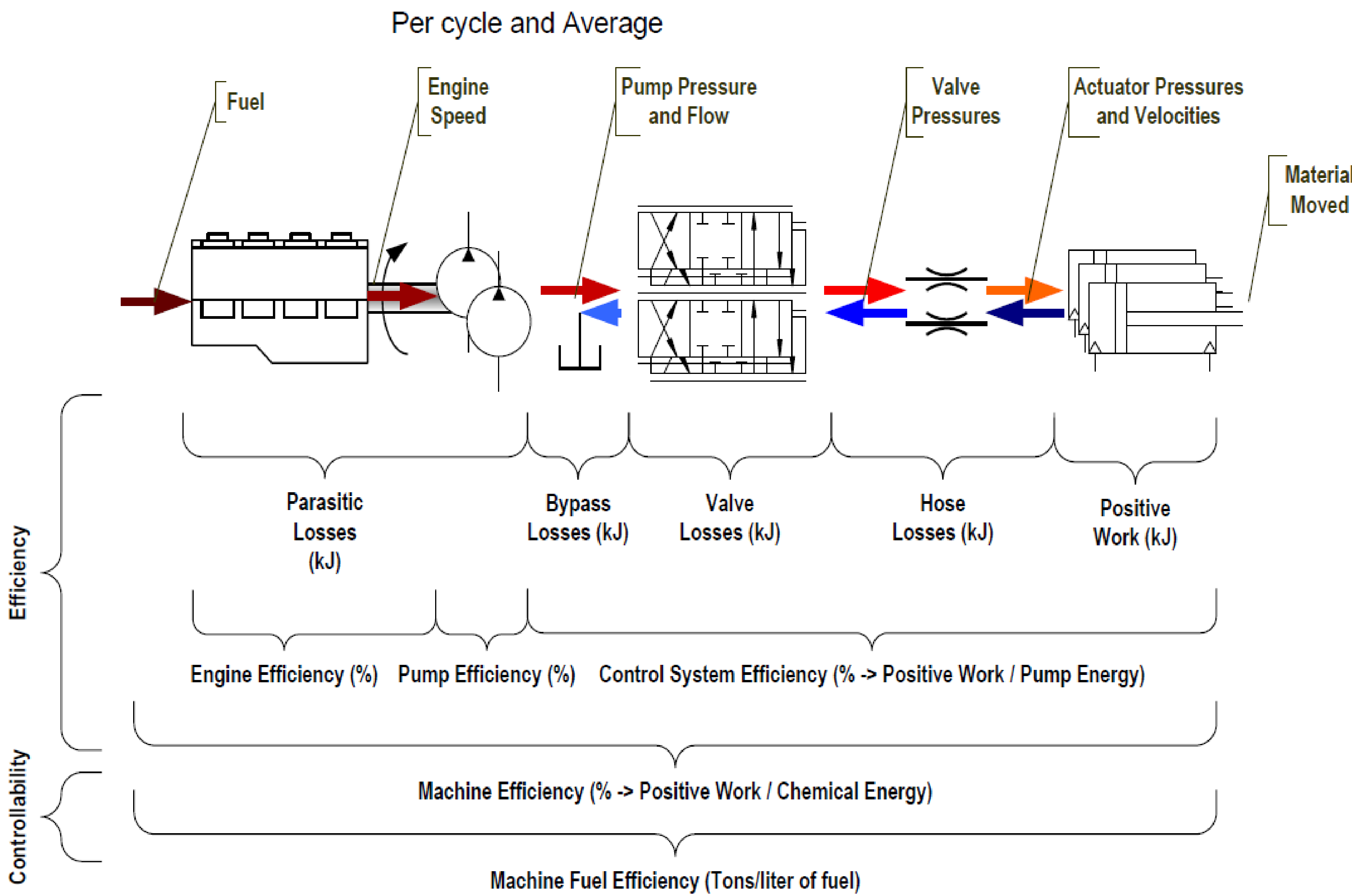


Total Transportation Sector in 2016 = 27.8 quads

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

Generated from ORNL Transportation Energy Data Book, Edition 35, Table 2.8

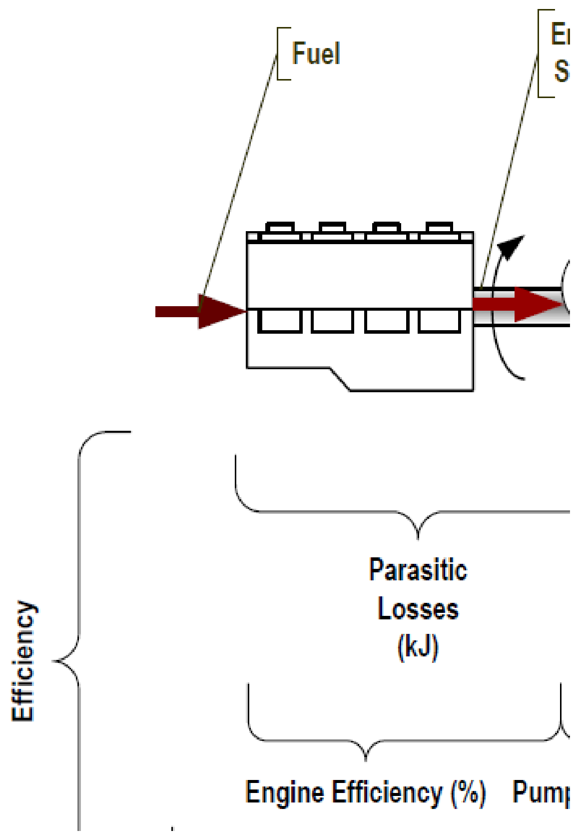
MOBILE FLUID POWER - EFFICIENCY

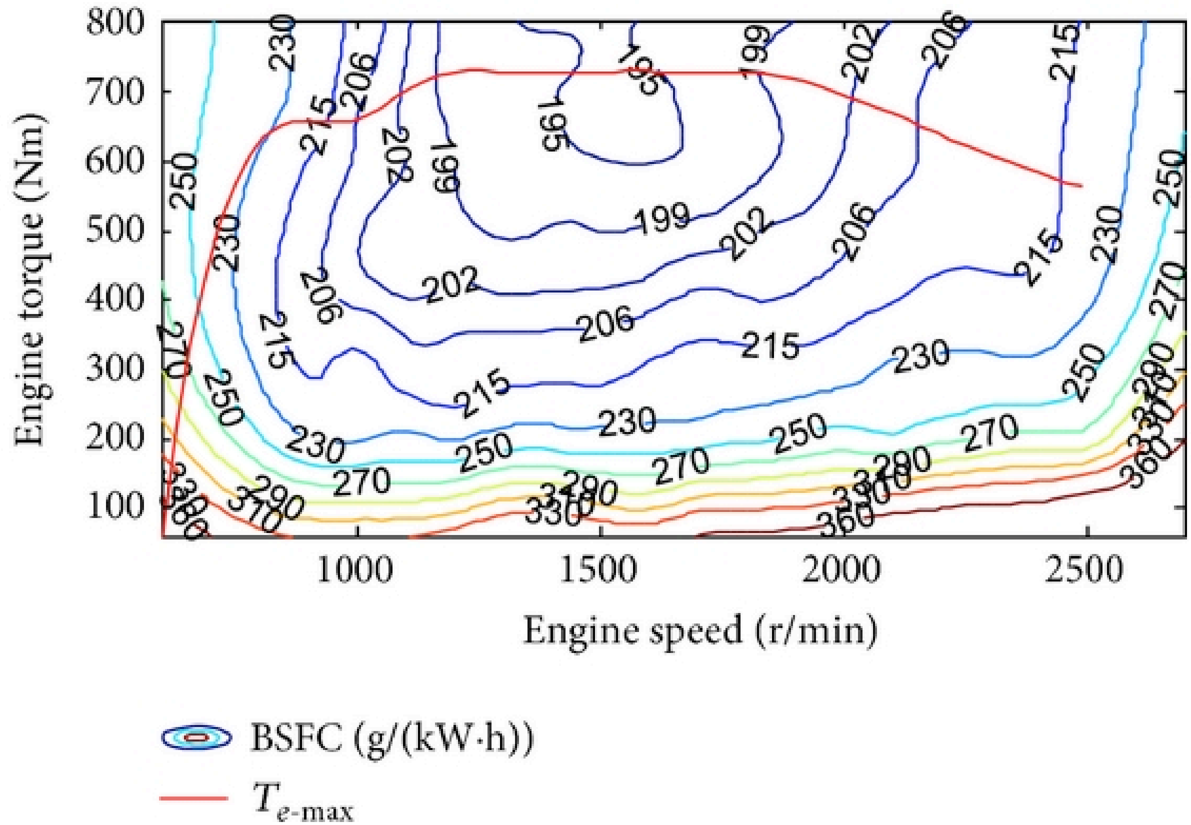


P. Achten, T. Brink, J. Potma, M. Schellekens, and G. Vael, "A Four-Quadrant Hydraulic Transformer for Hybrid Vehicles", The 11th Scandinavian International Conference on Fluid Power, Sweden, 2009.

MOBILE FLUID POWER - EFFICIENCY

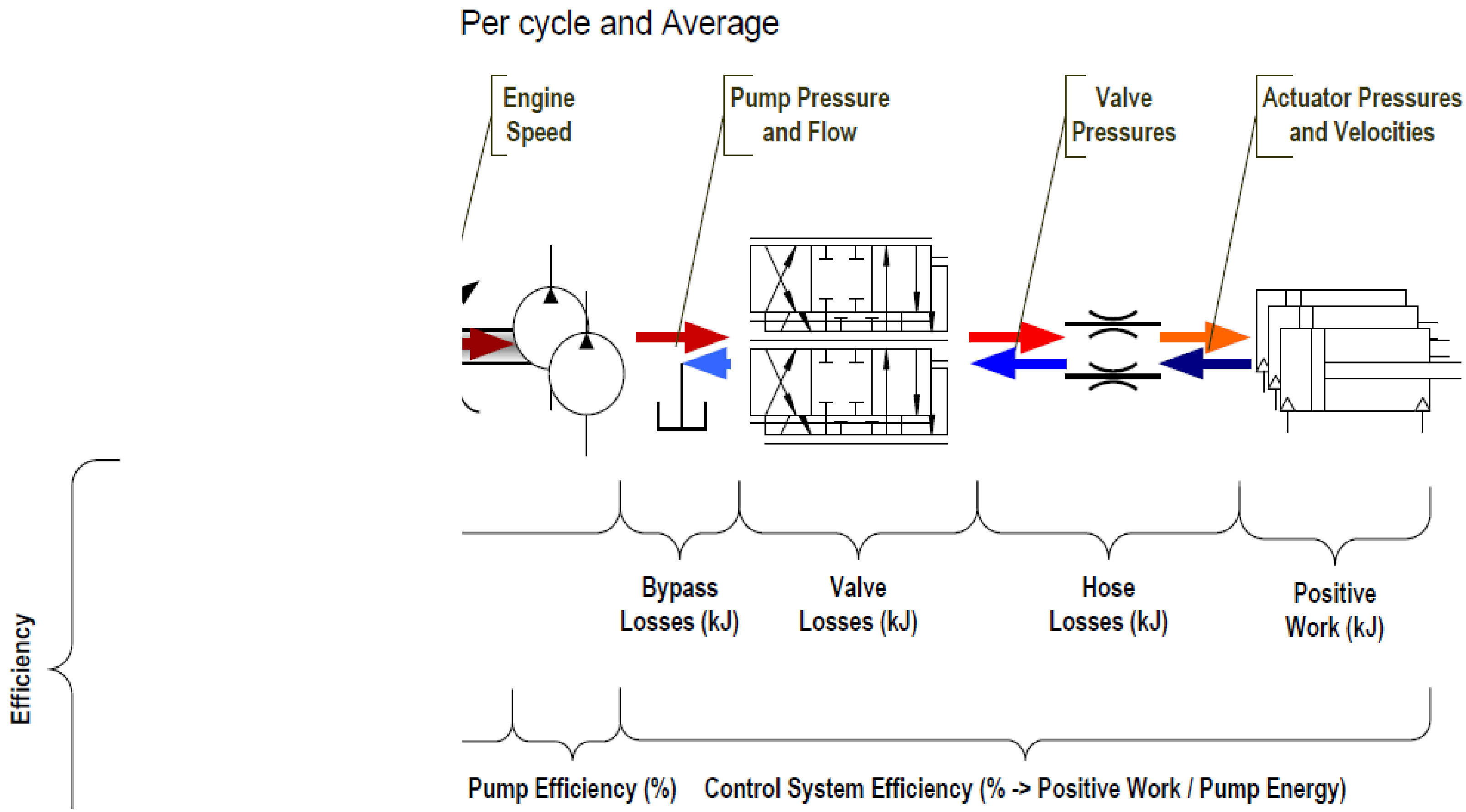
Per cycle and Average





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.

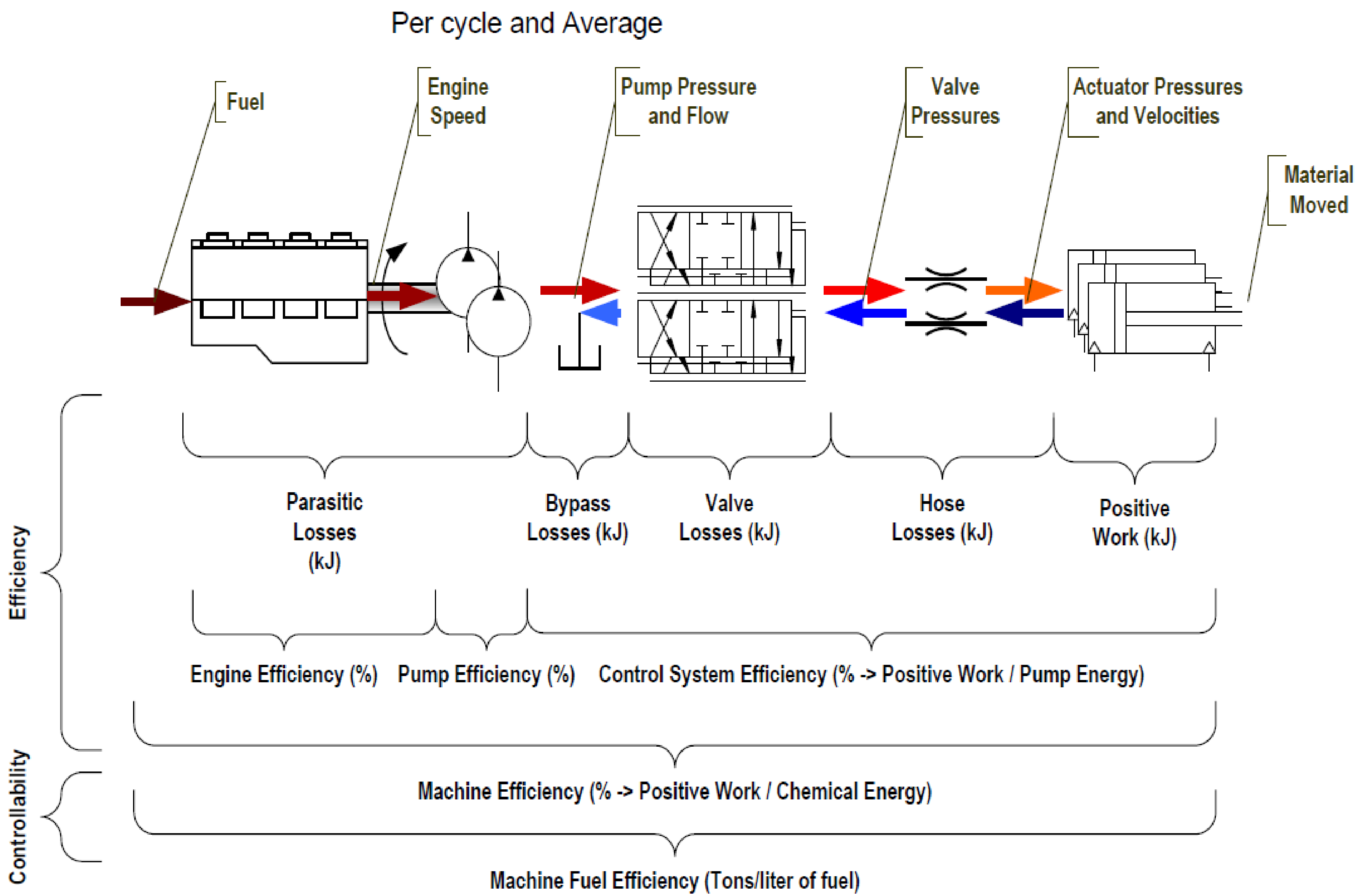
P. Achten, T. Brink, J. Potma, M. Schellekens, and G. Vael, “A Four-Quadrant Hydraulic Transformer for Hybrid Vehicles”, The 11th Scandinavian International Conference on Fluid Power, Sweden, 2009.



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]

1. P. Achten, T. Brink, J. Potma, M. Schellekens, and G. Vael, "A Four-Quadrant Hydraulic Transformer for Hybrid Vehicles", The 11th Scandinavian International Conference on Fluid Power, Sweden, 2009. 2. 2017 Industry interviews

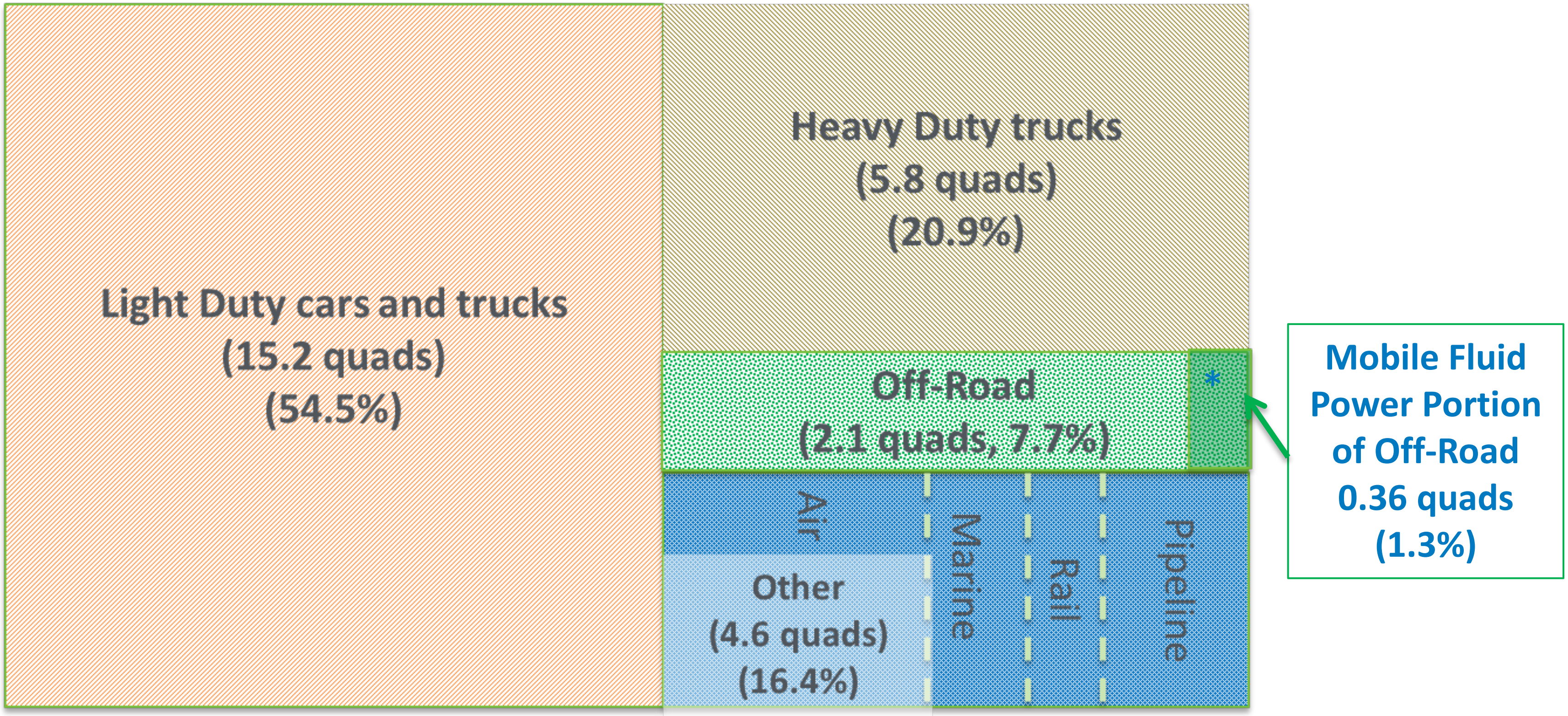
MOBILE FLUID POWER - EFFICIENCY



P. Achten, T. Brink, J. Potma, M. Schellekens, and G. Vael, "A Four-Quadrant Hydraulic Transformer for Hybrid Vehicles", The 11th Scandinavian International Conference on Fluid Power, Sweden, 2009.

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



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

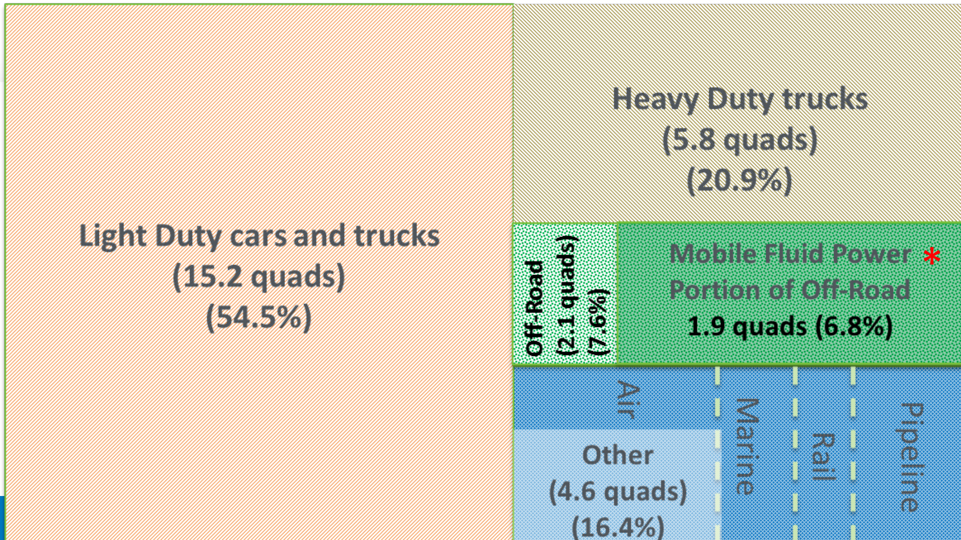
Off-Highway Transportation-Related Fuel Consumption from the Nonroad Model, 2014 (trillion Btu)

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

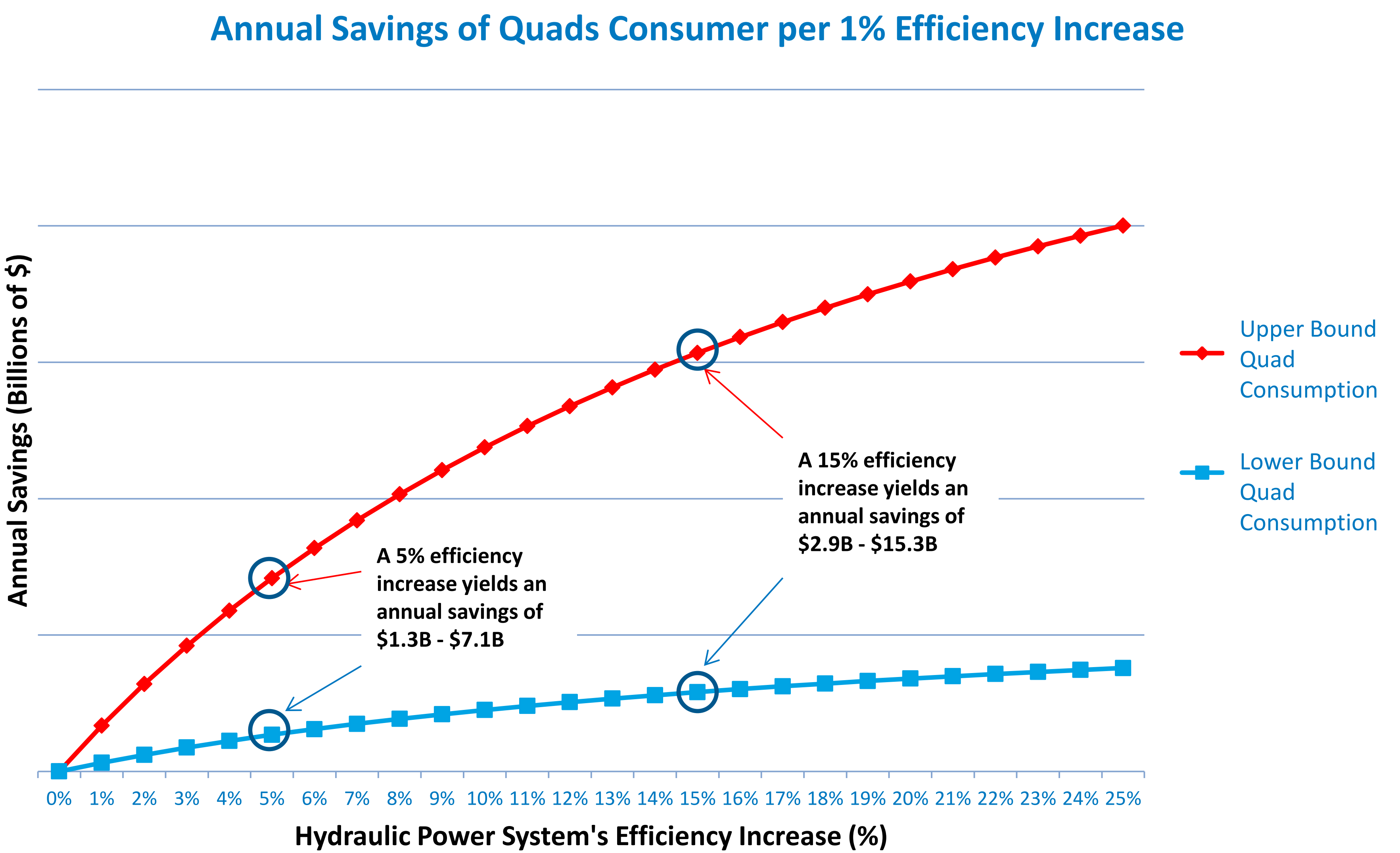
Source:
Environmental Protection Agency, MOVES2014a model, www.epa.gov/otaq/models/moves.

- 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



POTENTIAL IMPACTS OF IMPROVED EFFICIENCY



Improvements from a 21% efficient fluid power system

NREL's MOBILE FLUID POWER STUDY

- **Preliminary Results:**
  - Construction and Agriculture dominate the mobile off-highway fluid power market
  - 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
  - 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
  - Energy Consumption Range of 0.36 – 1.9 quads per year resulting in $7B-$36.8B per year
  - A 5% efficiency increase produces a potential of $1.3B – $7.1B savings per year
  - 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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- Travis Peterson, Walvoil Fluid Power
- Tony Zingman, Wandfluh of America
- Sean McCarthy, World Wide Fittings
- Steve Cavera, Yates Industries

Roadmap Elements

Customer Driver ← **Research Challenge** ← **Research Target**

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

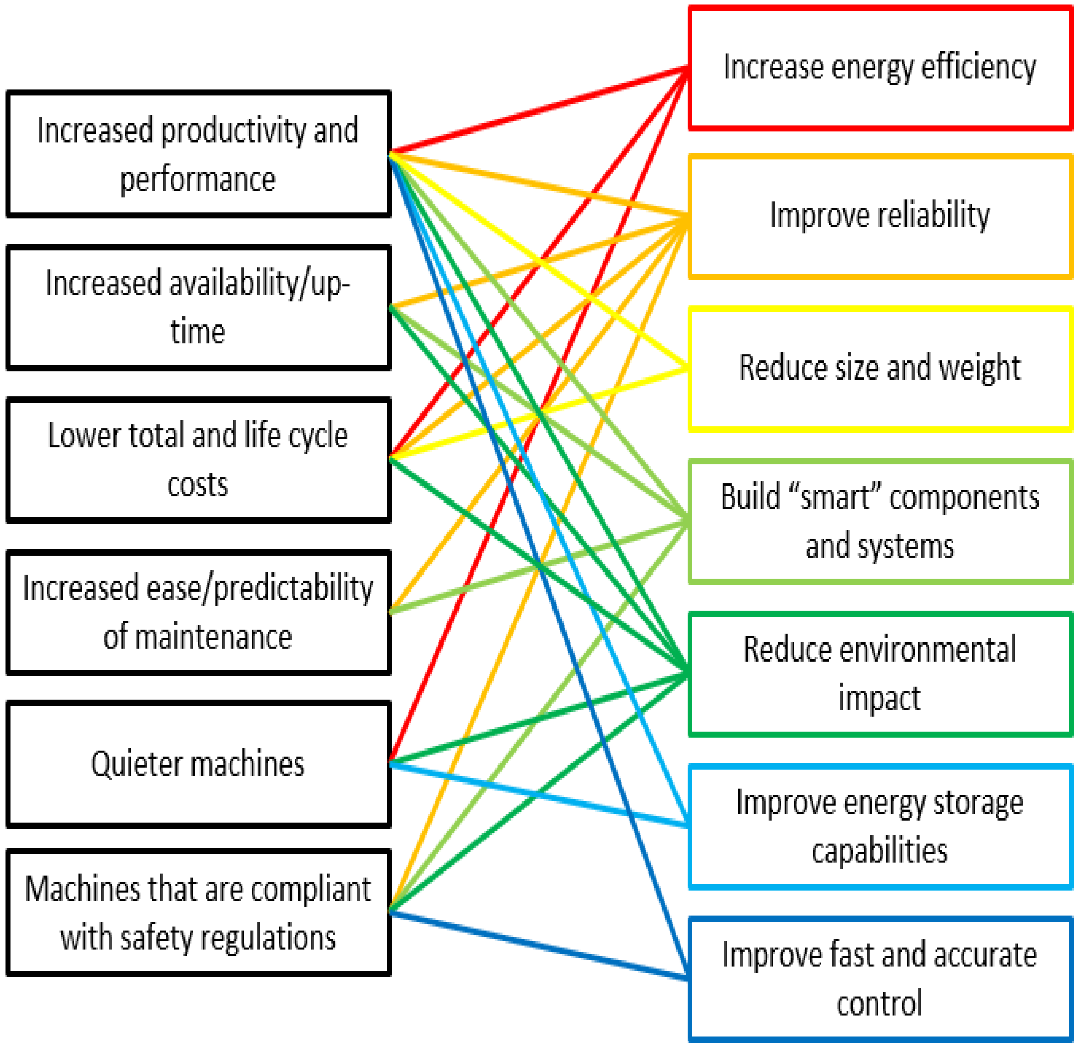
The broad areas of attention that must be addressed if fluid power is to meet or better meet the customer needs described by the drivers.

Research Target

The objectives that quantify or otherwise describe successful pre-competitive strategies for pursuing the research challenges

Customer Drivers/Research Challenges

Customer Drivers | **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.

NATIONAL FLUID POWER ASSOCIATION · NFPA ·

CENTER FOR COMPACT AND EFFICIENT FLUID POWER
A National Science Foundation Engineering Research Center

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

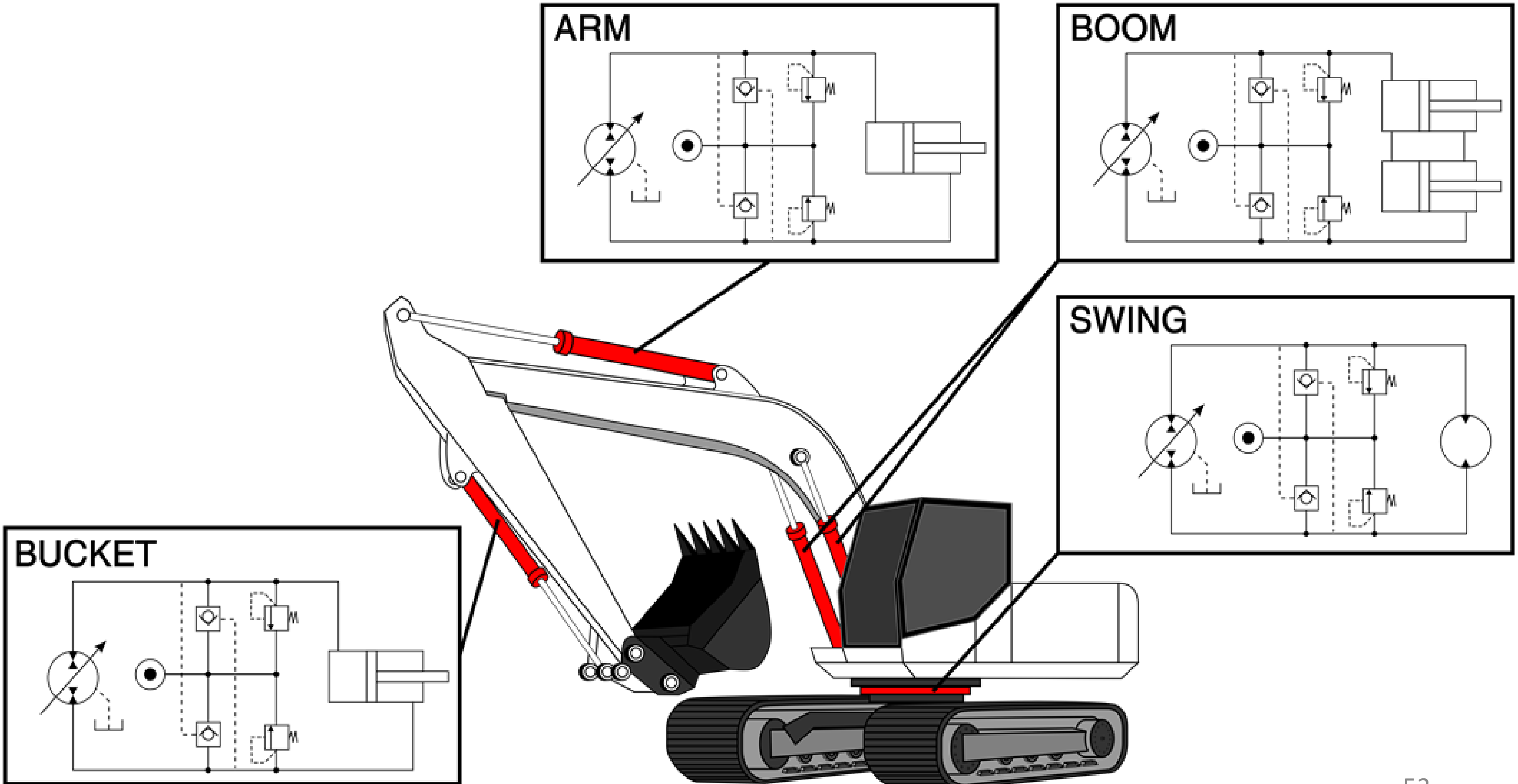
- Focus on wheel loaders and excavators… they consume the most energy
- Efficiently match required pressures to different loads
- Expand the use of energy recovery
  - Energy variations within a duty cycle provide opportunities for recovery. Repeatable cycles are easiest.
- Operate engine and hydraulics 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

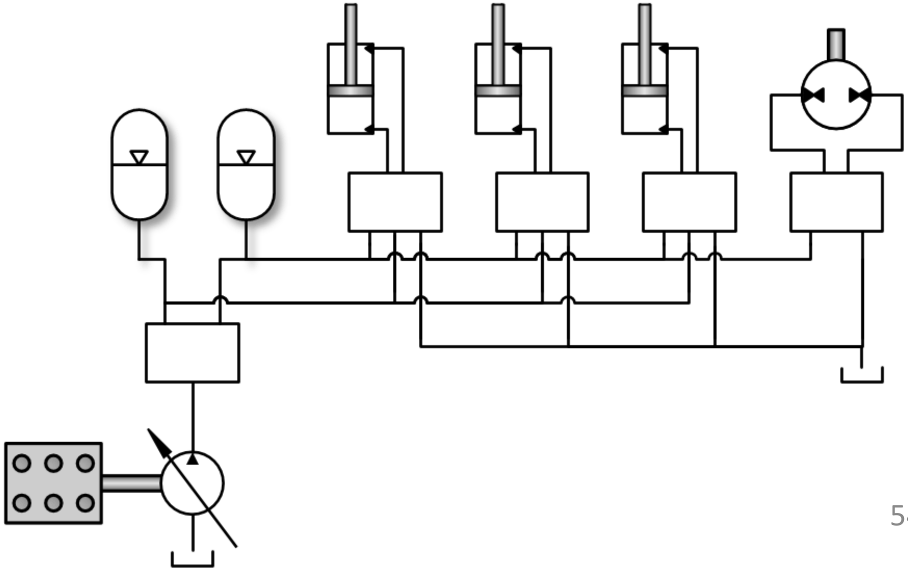
Purdue Displacement Controlled Architecture

- 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.

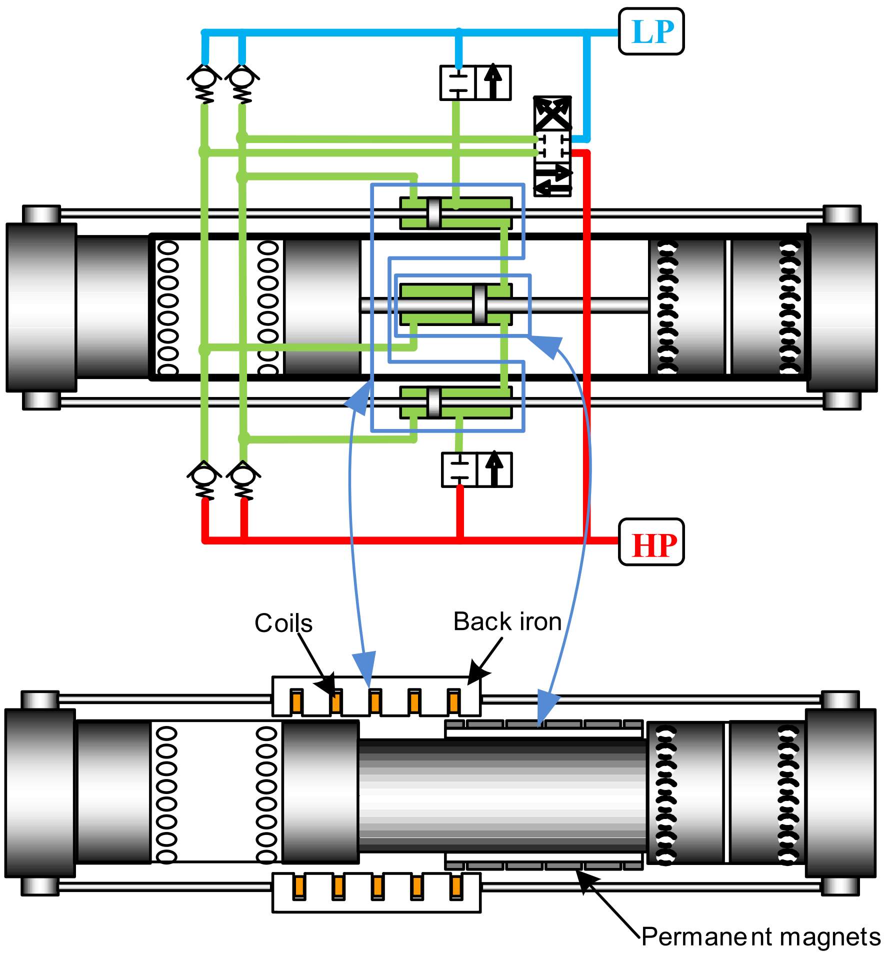


IFAS Aachen STEAM Architecture

- 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

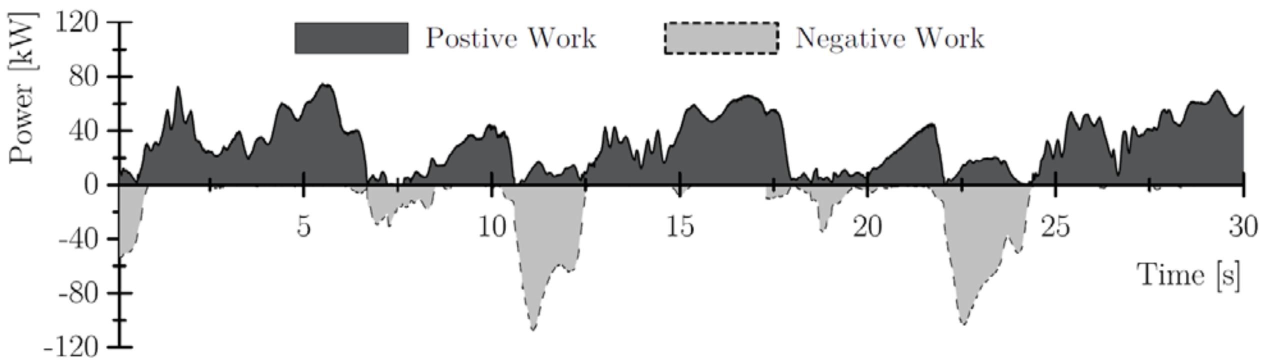


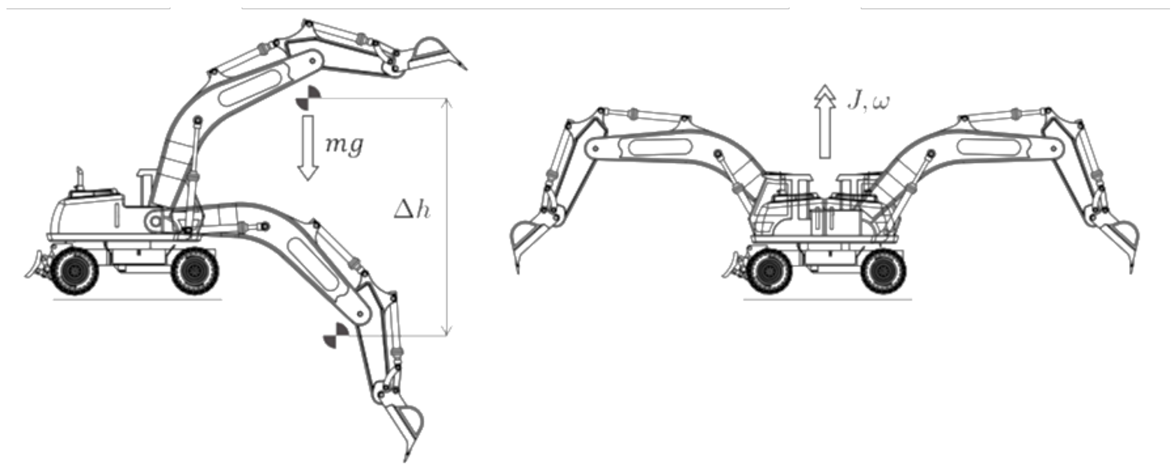
- Opposed Piston Opposed Cylinder (OPOC) Design
- Direct Injection
- Uniflow scavenging
- HCCI combustion

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

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



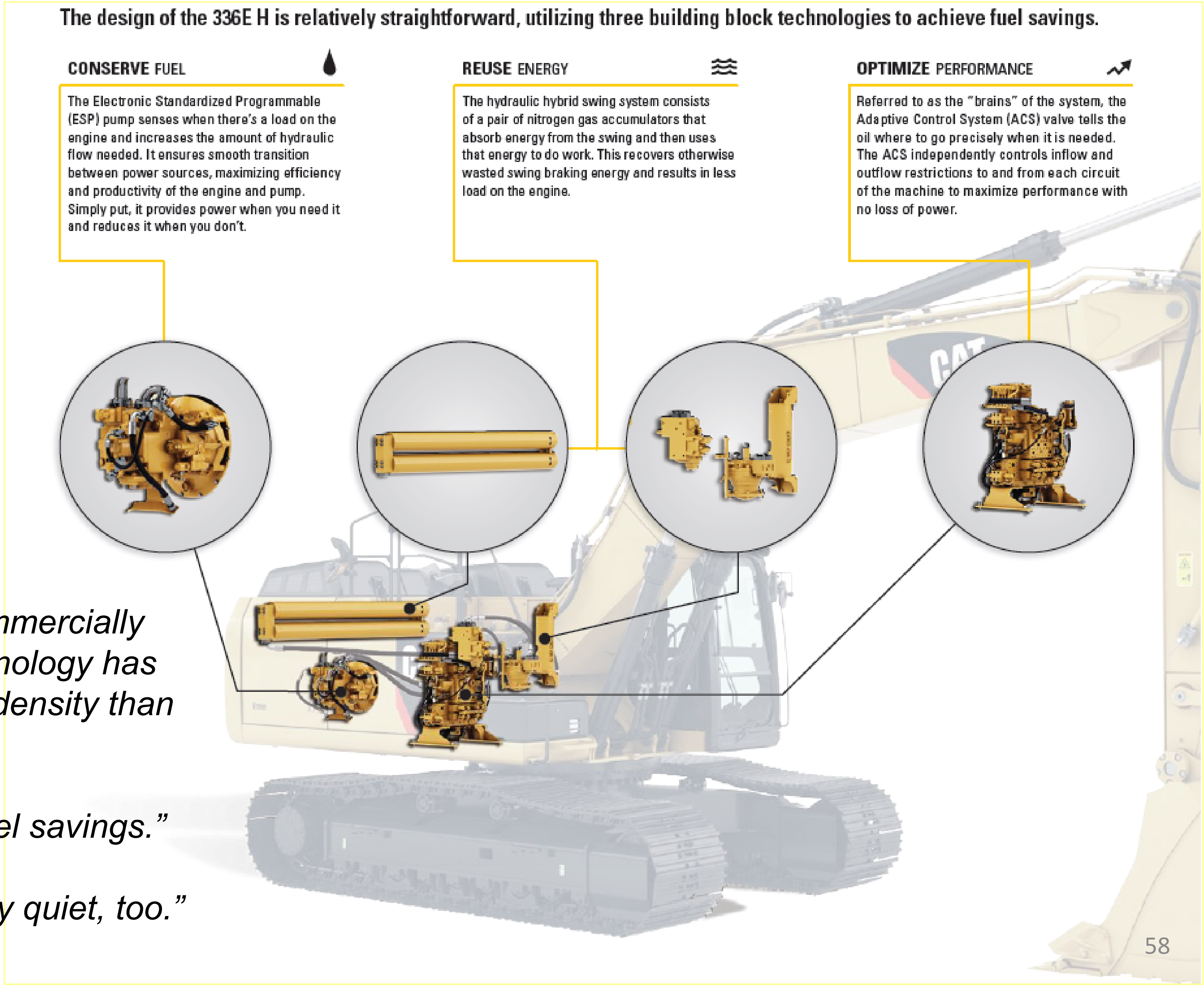


Excavator boom and swing recovery hybrids

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

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."

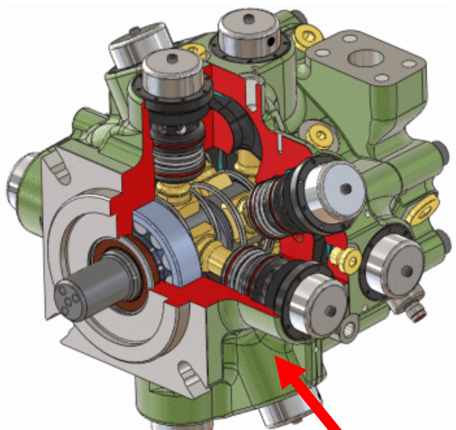
"Up to 25% fuel savings."

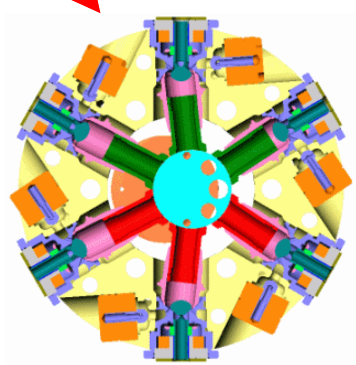
"Extraordinarily quiet, too."

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

CCEFP

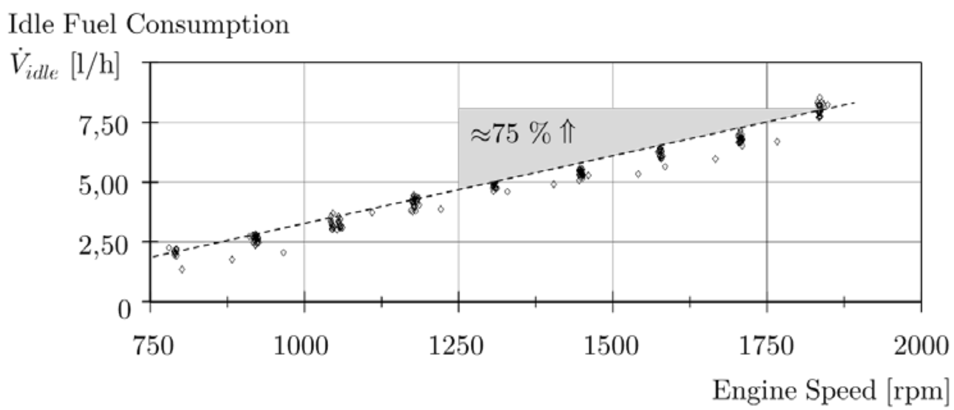
- 26-ton Caterpillar crawler excavator in comprehensive tests
- Accurate recording of the saving potential depending on the type of use
- Statistically valid data generated

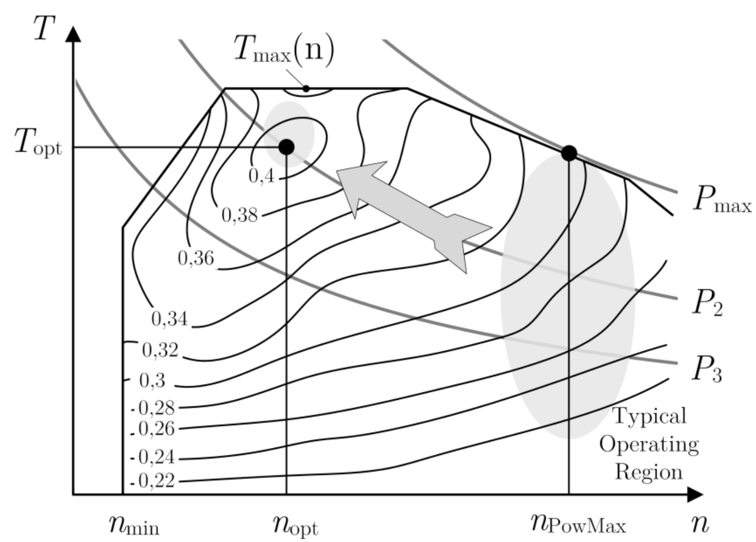
	Fuel consumption per cycle	Efficiency increase (buckets per liter of fuel)	Productivity increase (buckets per cycle)
Leveling	–	Up to 4%	–
Drive mode (meters)	–	Up to 11 %	Up to 8 %
Digging (at full speed)	Up to 3%	Up to 15 %	Up to 15 %

EVONIK
POWER TO CREATE

Engine Management

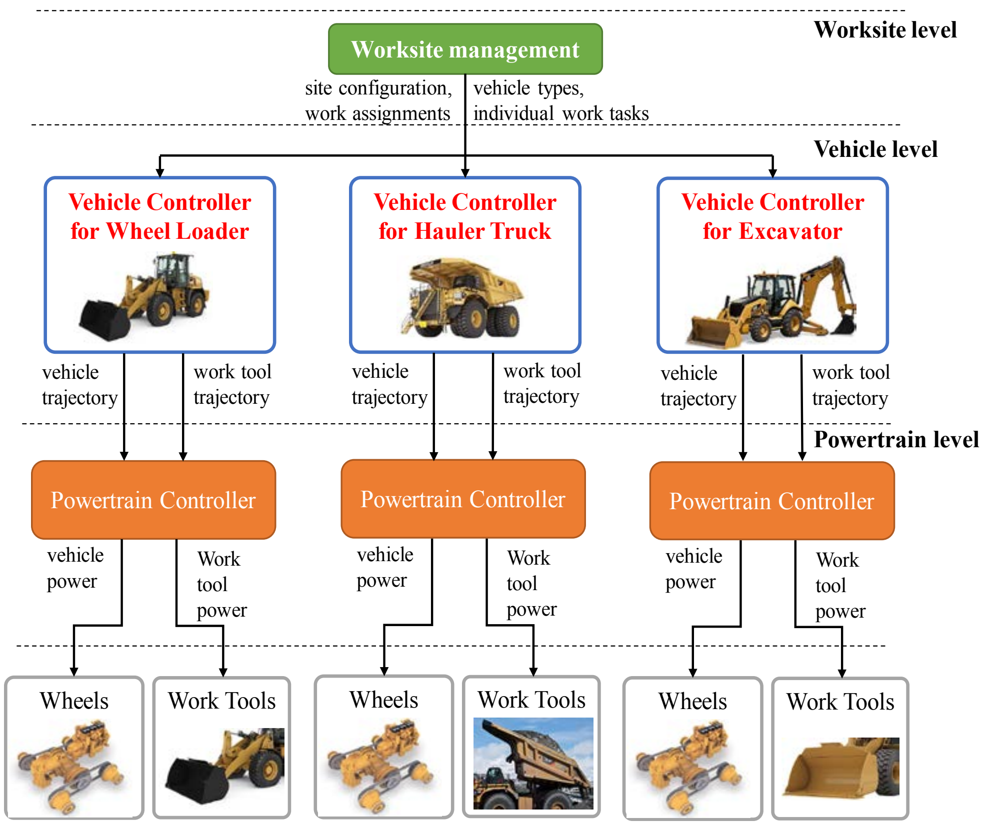
- Engine typically operates at high speed
- Additional power source from hybridization required to reduce engine speed
- More efficient operation of engine and pump in sweet point
- Reduce "high idle" fuel rate
- On/Off operation possible with hybridization





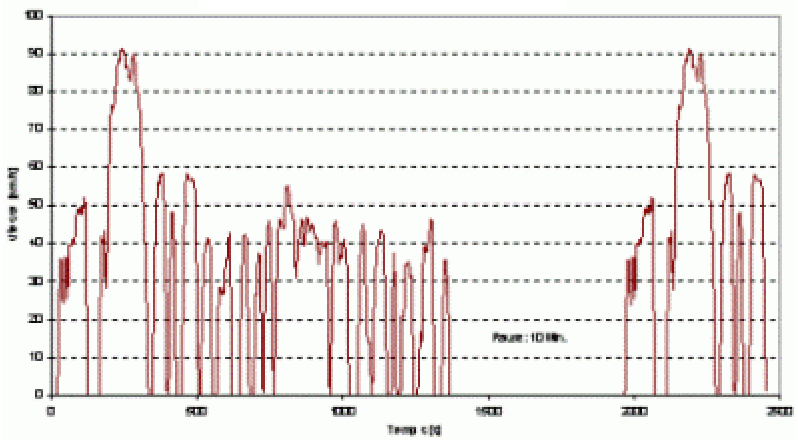
Connected and Autonomous Off-Road Vehicles

- 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

Cycle US FTP75



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

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