Reciprocating Internal Combustion Engines

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University of Wisconsin-Madison

2014 Princeton-CEFRC
Summer School on Combustion
Course Length: 15 hrs

(Mon.- Fri., June 23 – 27, 2014)

Short course outine:

Engine fundamentals and performance metrics, computer modeling supported by in-depth understanding of fundamental engine processes and detailed experiments in engine design optimization.

Day 1 (Engine fundamentals)
- Part 1: IC Engine Review, 0, 1 and 3-D modeling
- Part 2: Turbochargers, Engine Performance Metrics

Day 2 (Combustion Modeling)
- Part 3: Chemical Kinetics, HCCI & SI Combustion
- Part 4: Heat transfer, NOx and Soot Emissions

Day 3 (Spray Modeling)
- Part 5: Atomization, Drop Breakup/Coalescence
- Part 6: Drop Drag/Wall Impinge/Vaporization/Sprays

Day 4 (Engine Optimization)
- Part 7: Diesel combustion and SI knock modeling
- Part 8: Optimization and Low Temperature Combustion

Day 5 (Applications and the Future)
- Part 9: Fuels, After-treatment and Controls
- Part 10: Vehicle Applications, Future of IC Engines

Kokjohn, IJER 2011, SAE 2011, SAE 2009

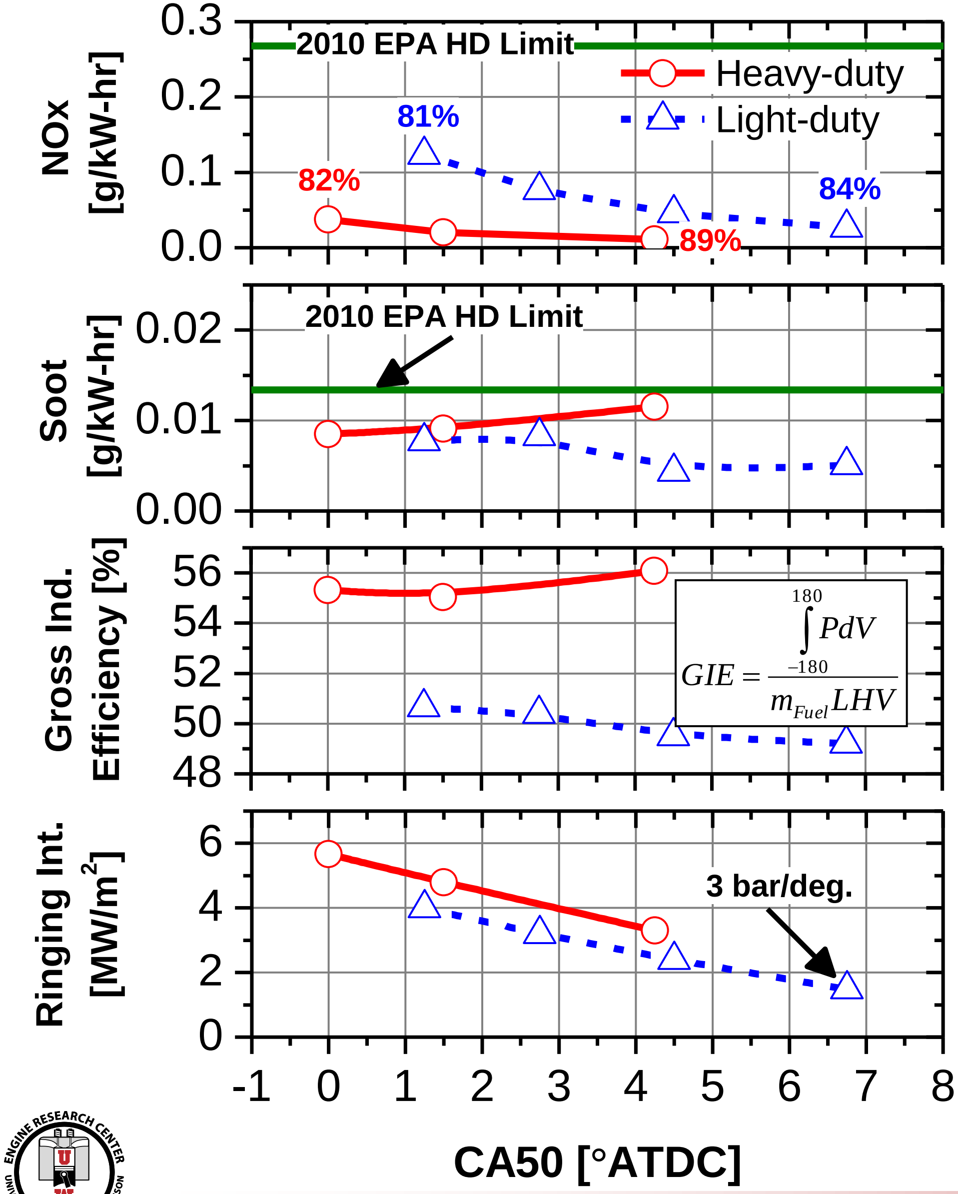
Light- & heavy-duty engine RCCI

- HD and LD engines compared over gasoline/diesel fuel ratio sweep at 9 bar IMEP
- LD engine intake temperature and pressure adjusted in to match HD compression stroke
- Engine size scaling laws do not provide a scaling parameter for engine speed
  - Kinetics implies speeds should be equal (equal ignition delay)
  - To scale convective heat transfer, LD engine should be operated at ~3800 rev/min
  - Intermediate speed of 1900 rev/min selected

	Heavy Duty	**Light Duty**
Engine	CAT	GM 1.9 L
IMEP (bar)	9	
Engine speed (rev/min)	1300	1900
Mean piston speed (m/s)	7.2	5.7
Total fuel mass (mg)	94	20.2
EGR (%)	41	
Premixed gasoline (%)	82 to 89	81 to 84
Diesel SOI 1 (° ATDC)	-58	-56
Diesel SOI 2 (° ATDC)	-37	-35
Diesel inj. pressure (bar)	800	500
Intake pressure (bar)	1.74	1.86
Intake runner temp. (° C)	32	39
Air flow rate (kg/min)	1.75	0.46
Abs. exhaust back pressure (bar)	1.84	1.98
Ave. exhaust temperature (° C)	271	319
Equivalence ratio (-)	0.52	0.62
Port-injected fuel	Gasoline	
Direct-injected fuel	Diesel Fuel	

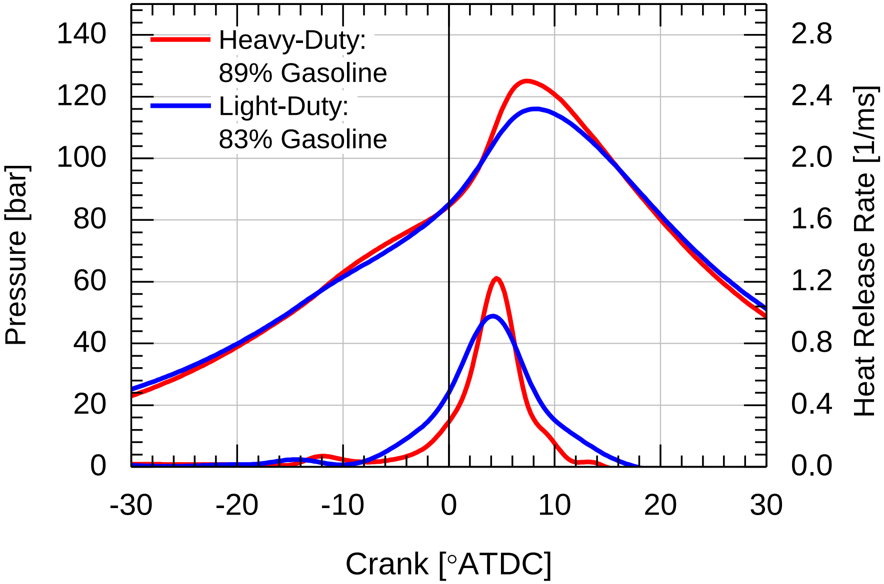
Kokjohn, IJER 2011
Kokjohn, SAE 2011

Light- & heavy-duty engine RCCI



$$GIE = \frac{\int_{-180}^{180} PdV}{m_{Fuel} LHV}$$

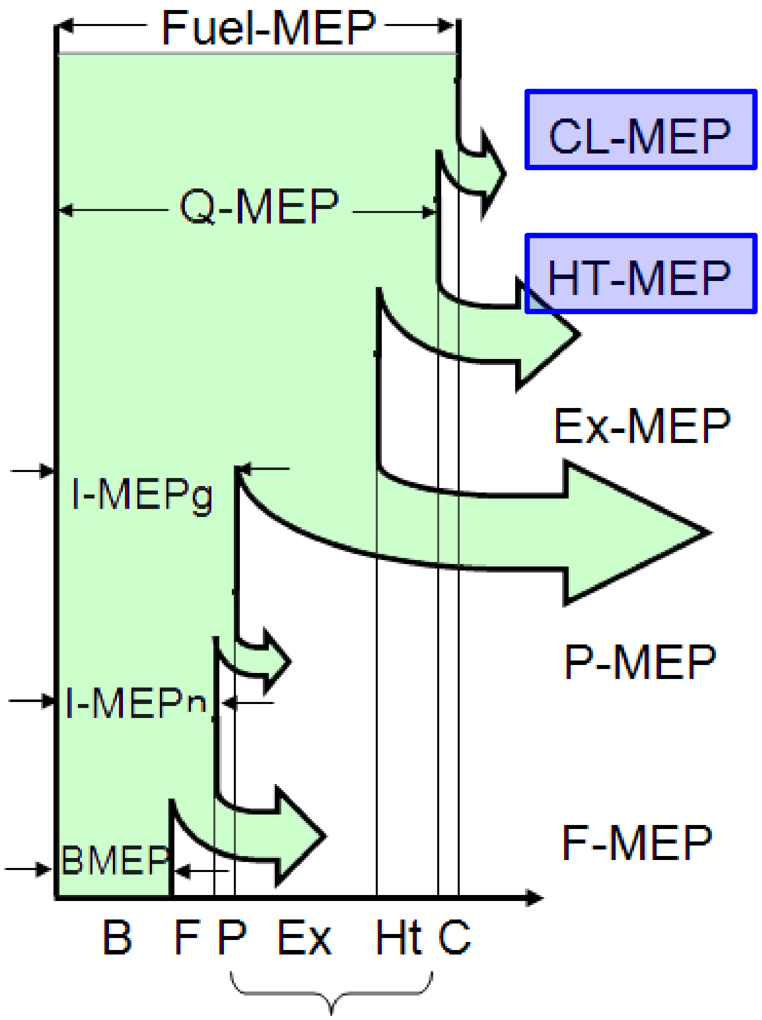
- Low NOx and soot emissions achieved for both HD and LD engines
- Ringing intensity (noise) easily controlled by combustion phasing (via gasoline-diesel ratio) with only minimal effect on efficiency
- Both engines achieve high efficiency; however, **HD engine shows 5 to 7% higher gross indicated efficiency**

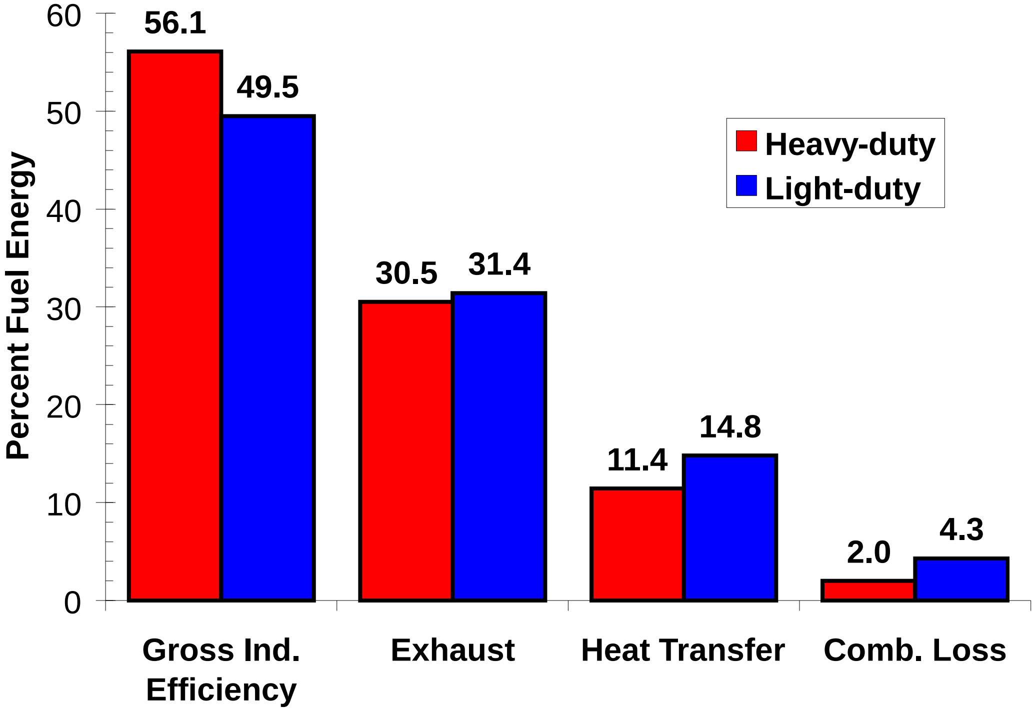


HD Conv. Diesel Efficiency = 48%
LD Conv. Diesel Efficiency = 45%

Kokjohn, IJER 2011
Kokjohn, SAE 2011

Light- & heavy-duty engine RCCI





- Gross indicated efficiency is lower in LD engine due to lower combustion efficiency and higher heat transfer losses
- Combustion efficiency is ~2% lower in LD engine
- 3.4% more of the fuel energy is lost to heat transfer in LD engine.

Kokjohn, IJER 2011
Kokjohn, SAE 2011

CFD modeling to explain losses

Combustion Losses

CFD modeling predicts that the highest levels of late cycle CO and UHC are located in the ring-pack crevice and near liner region

- Reducing ring-pack crevice volume improves combustion efficiency

  (SAE 2012-01-0383)

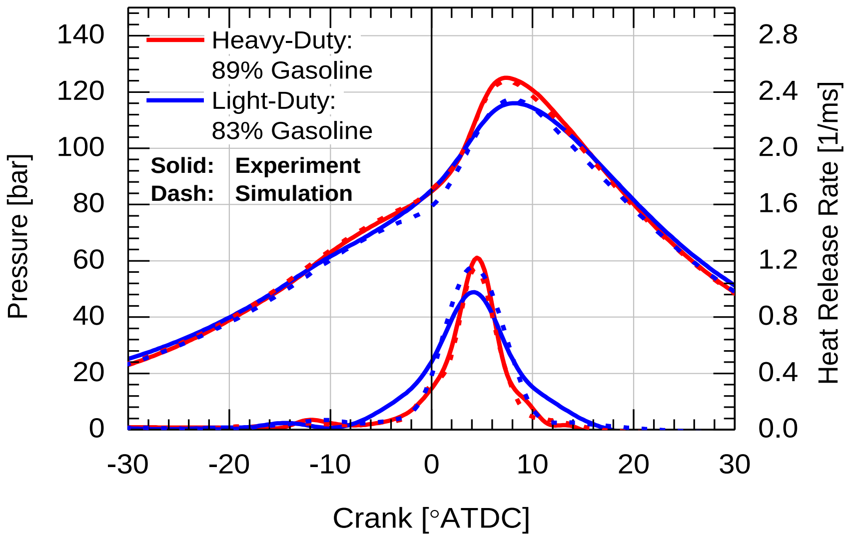
Heat Transfer Losses

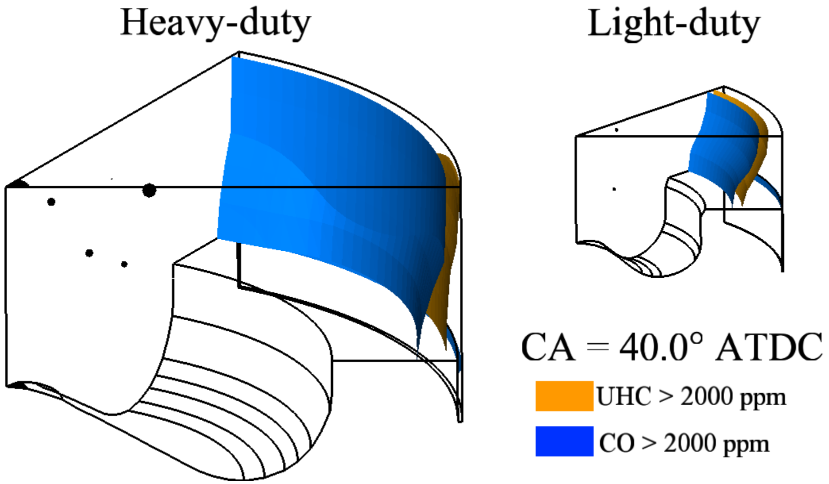
LD engine heat transfer is higher due to

- Higher swirl (**LD: 2.2** **HD: 0.7**)
- Increased surface area-to-volume ratio (**LD: 5.6** **HD: 2.7**)
- Lower mean piston speed

  (**LD: 5.7 m/s** **HD: 7.2 m/s**)

CFD simulations with KIVA-Chemkin code and reduced PRF mechanism





Kokjohn, 2012

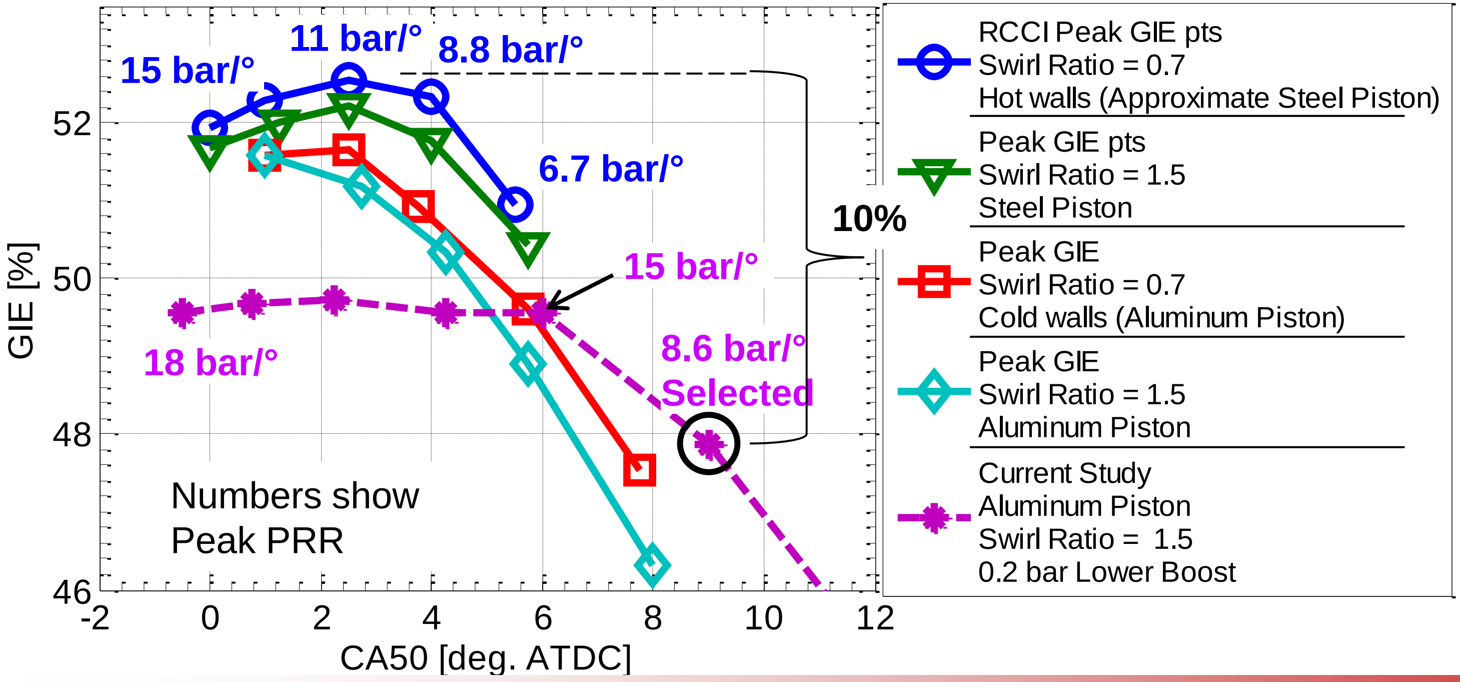
Future research directions

LD RCCI further improved by relaxing constraints (Euro 4 boost, IMT, swirl..)

Peak efficiency at Mode 5 is 47.9% → CFD says can be increased to ~53%

Improve heat transfer losses and combustion phasing

- Higher boost (1.86 bar vs. 1.6 bar) allows CA50 advance with same PRR and lowers heat transfer losses due to lower Φ (lower temps)
- Lower swirl reduces convective heat transfer losses
- Higher wall temps improve combustion efficiency (steel piston)
- 8% + 10% ~ consistent with DOE goals of 20-40% improvement



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UW-Madison RCCI series hybrid vehicle

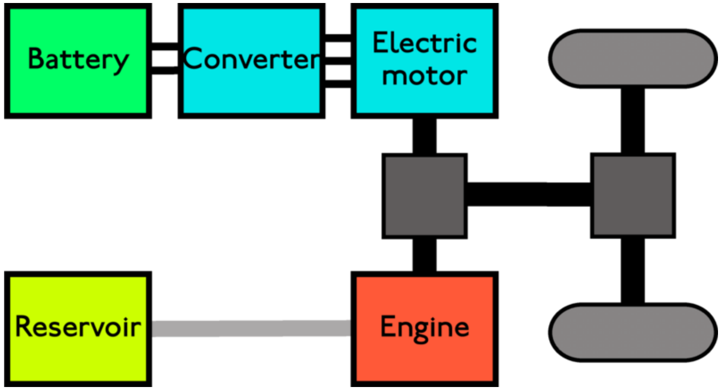
2009 Saturn Vue, V6 FWD base model → GM 1.9L diesel engine

Installation of 7.5 gal. gasoline and diesel tanks

Hybrid vehicle architecture

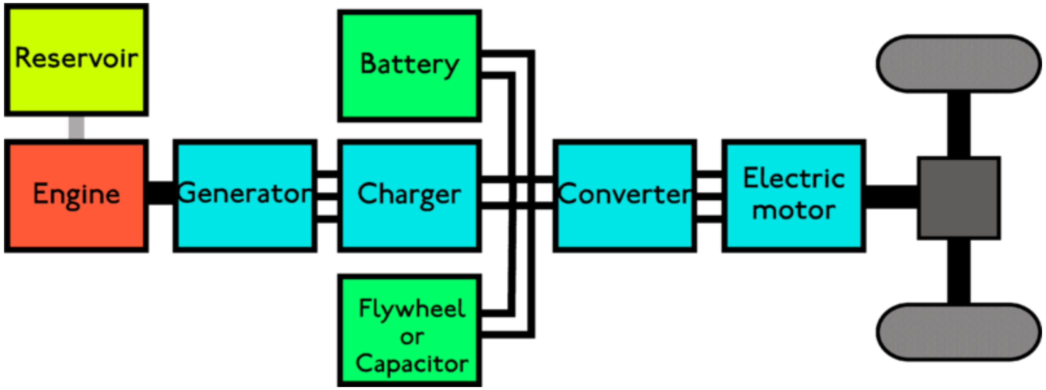
Parallel Hybrid

Engine always drives the wheels, electric motor is an assist (Honda Insight).



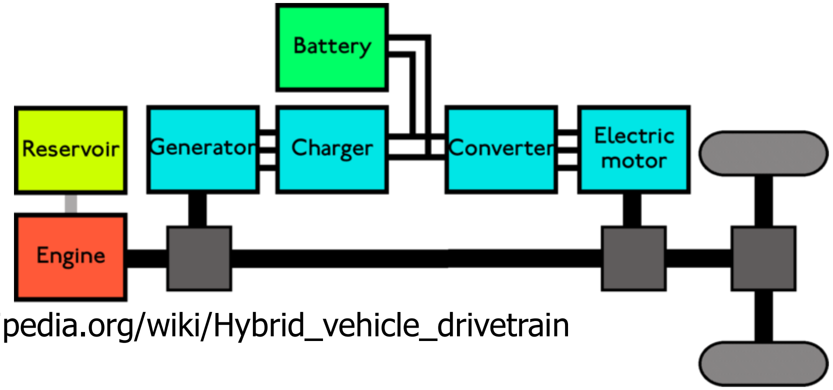
Series Hybrid

Engine is not mechanically coupled to the drive train.
Engine drives a generator to produce electricity which drives the vehicle by an electric motor
(UW Hybrid design)



Power-Split (series/parallel)

Is a combination of both designs.
Can drive on electric only or engine only or a combination of both.
(Toyota Prius)



http://en.wikipedia.org/wiki/Hybrid_vehicle_drivetrain

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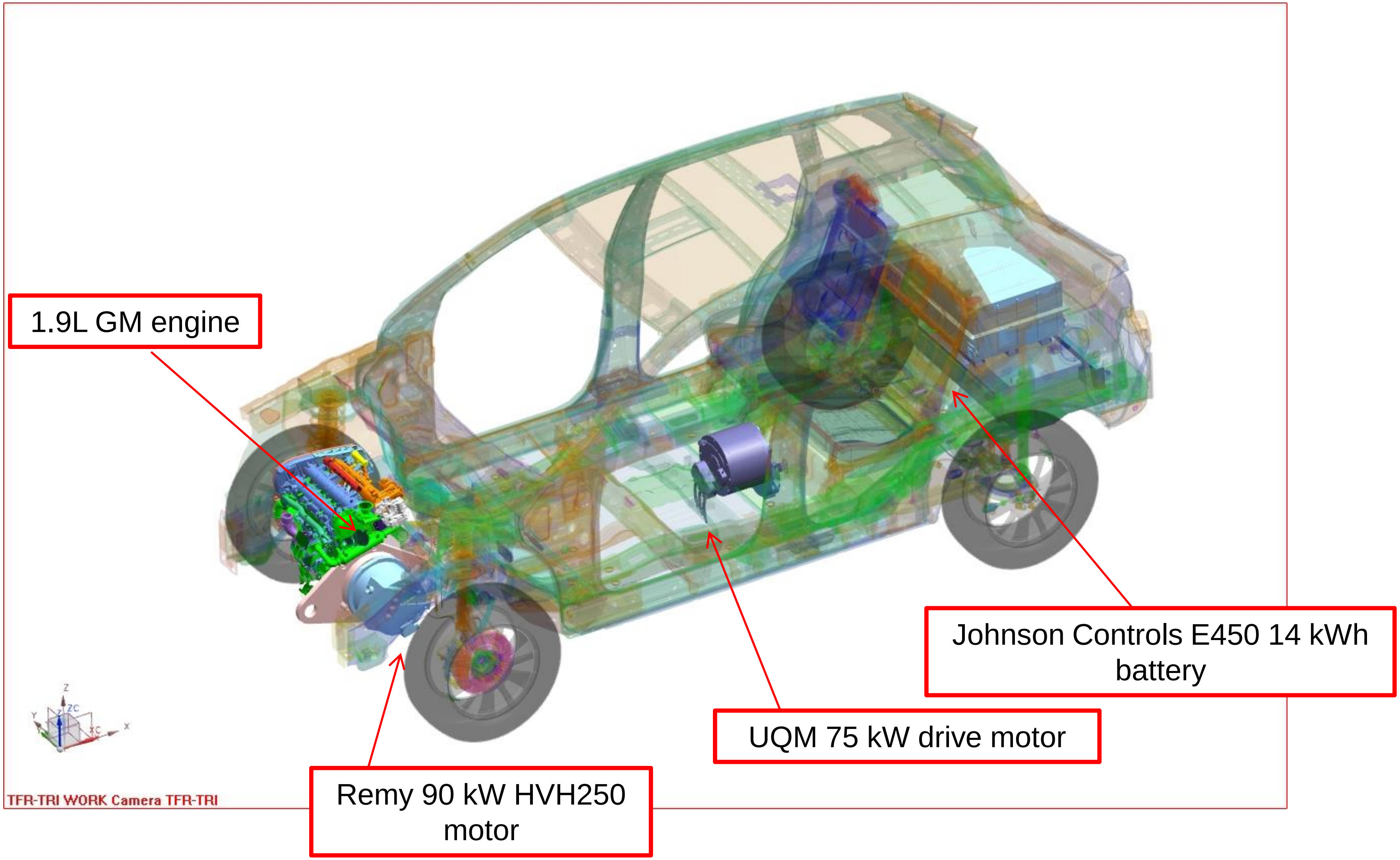
UW-Madison RCCI series hybrid vehicle architecture



1.9L GM engine

Johnson Controls E450 14 kWh battery

UQM 75 kW drive motor

Remy 90 kW HVH250 motor

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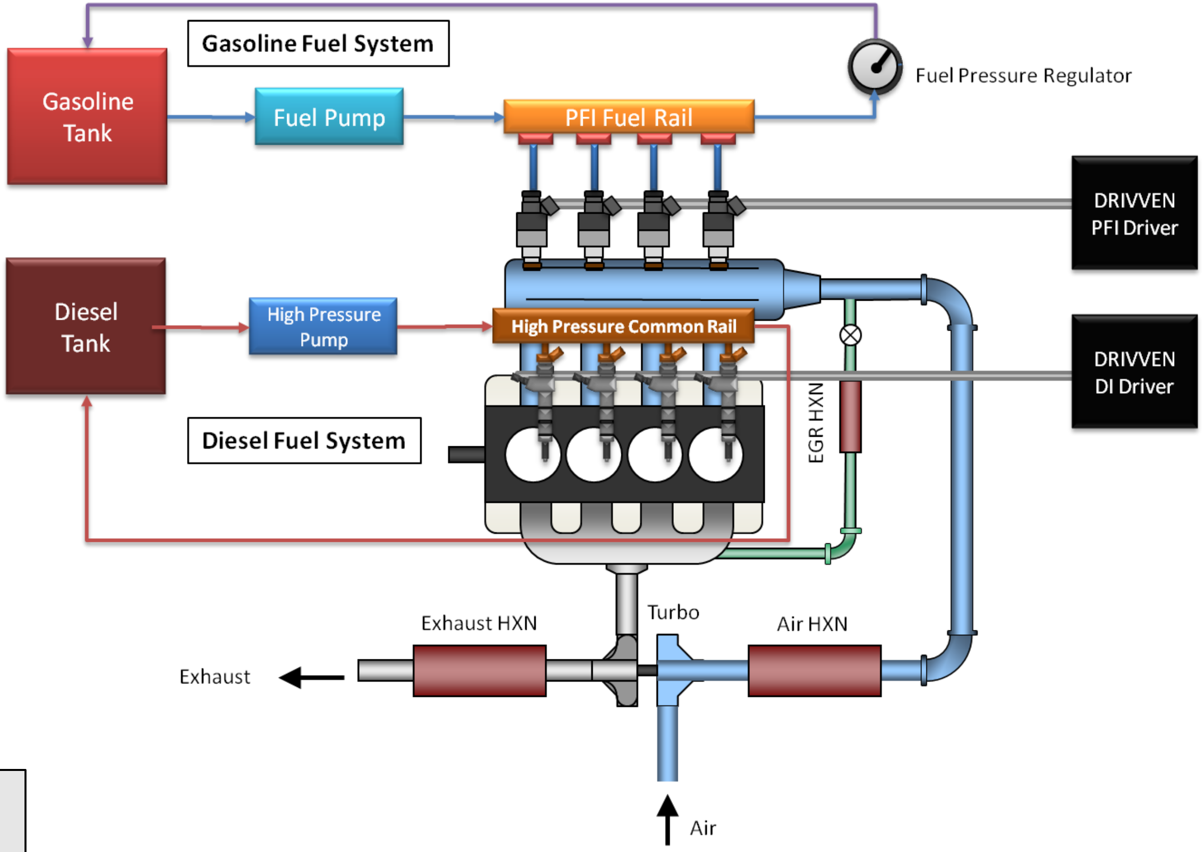
RCCI engine configuration

GM 1.9L Geometry

Number of Cylinders	**4**
Bore (mm)	**82.0**
Stroke (mm)	**90.4**
Compression Ratio (stock)	**17.5**
Compression Ratio (RCCI piston)	**15.1**
Rated Power (kW)	**110**
Rated Torque (Nm)	**315**

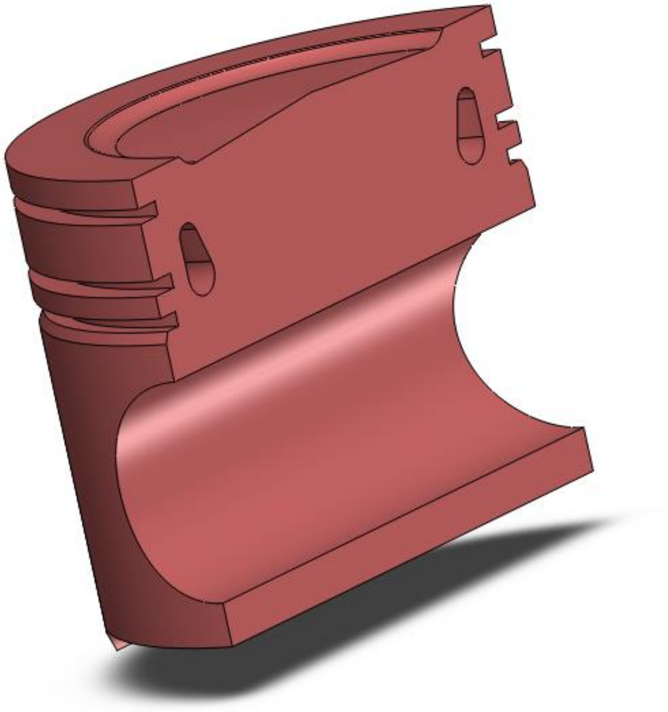
PFI Fuel - 96 RON gasoline
DI Fuel – 46 CN ULSD

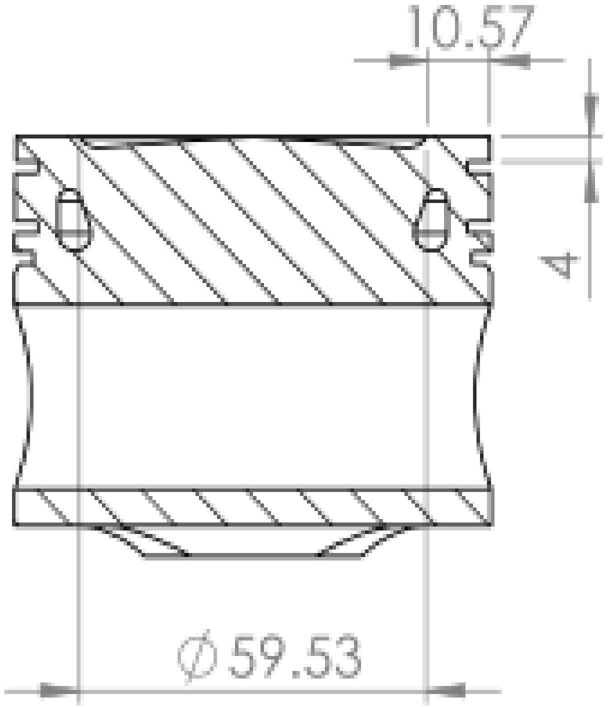


RCCI piston design

For the hybrid car, a next generation piston was designed to reduce the crevice volume in order to lower HC emissions.

15.1:1 CR and reduced surface area, with smaller crevice height (4mm vs 8mm).





Project goals

Vehicle testing at Ford Vehicle Emissions Research laboratory:

Compare UW hybrid with current PHEVs such as Ford Fusion and Chevy Volt over Federal Test Cycles (FTP75, HWFET and US06)

	Volt	**UW**
Drive Motor	**111 [kW]**	**75 [kW]**
Generator	**55 [kW]**	**90 [kW]**
HV battery	**16 [kWh]**	**14 [kWh]**
Inertia Weight	**4000 [lbm]**	**4000 [lbm, simulated]**

Shake down vehicle

- Test electric drive operation at high speed (i.e., US06)
- Starting the engine in RCCI mode
- Operate RCCI at different power levels over standard EPA test cycles
  (FTP, HWFET and US06)

Project methodology

Because Vue is heavy (~6,000 lbm) prototype, operation of a current PHEV with similar hardware was simulated.

For all tests, UW vehicle was simulated as a Ford Fusion (4,000 lbm inertia weight).

Results were compared with Volt fuel economy and emissions as they are publicly available and the vehicle drag coefficient is the same as the Ford (Cd =0.28)

Operated engine as charge sustaining for each entire test cycle

No attempt to pass emissions (no after-treatment system installed)

No regenerative braking to minimize number of times starting the engine

First ever test with new pistons and engine was not broken in

Modified RCCI calibration on the fly during the tests

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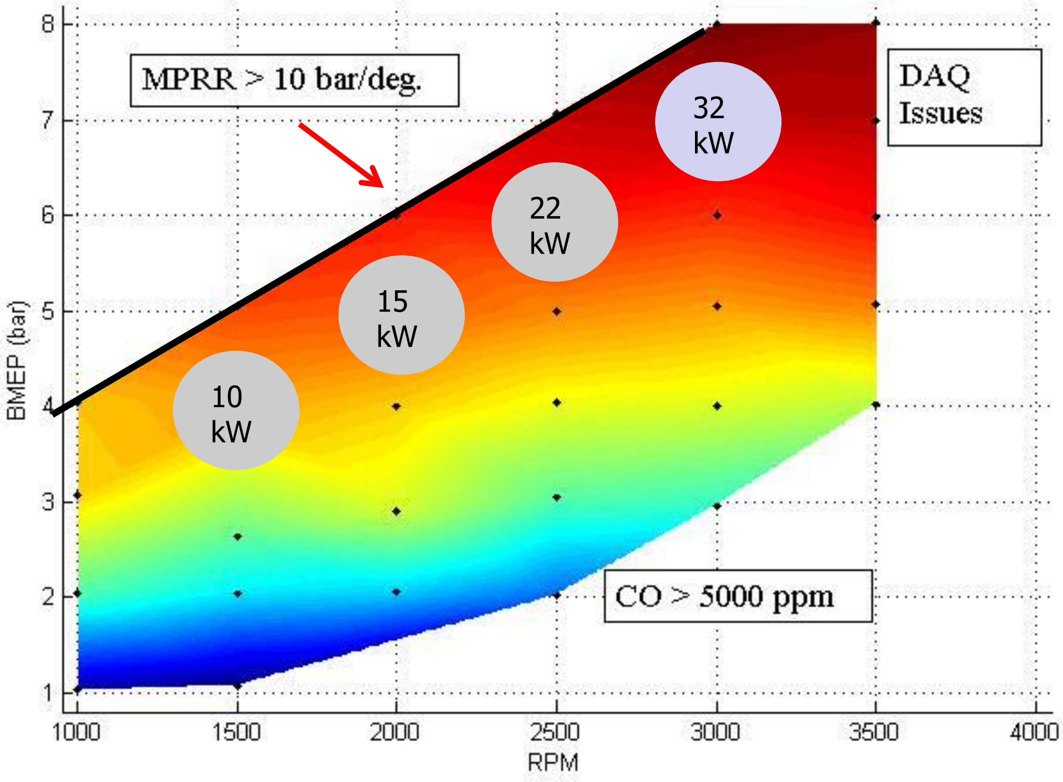
Hybrid RCCI operating conditions



RCCI operating conditions derived from steady-state results from ORNL testing

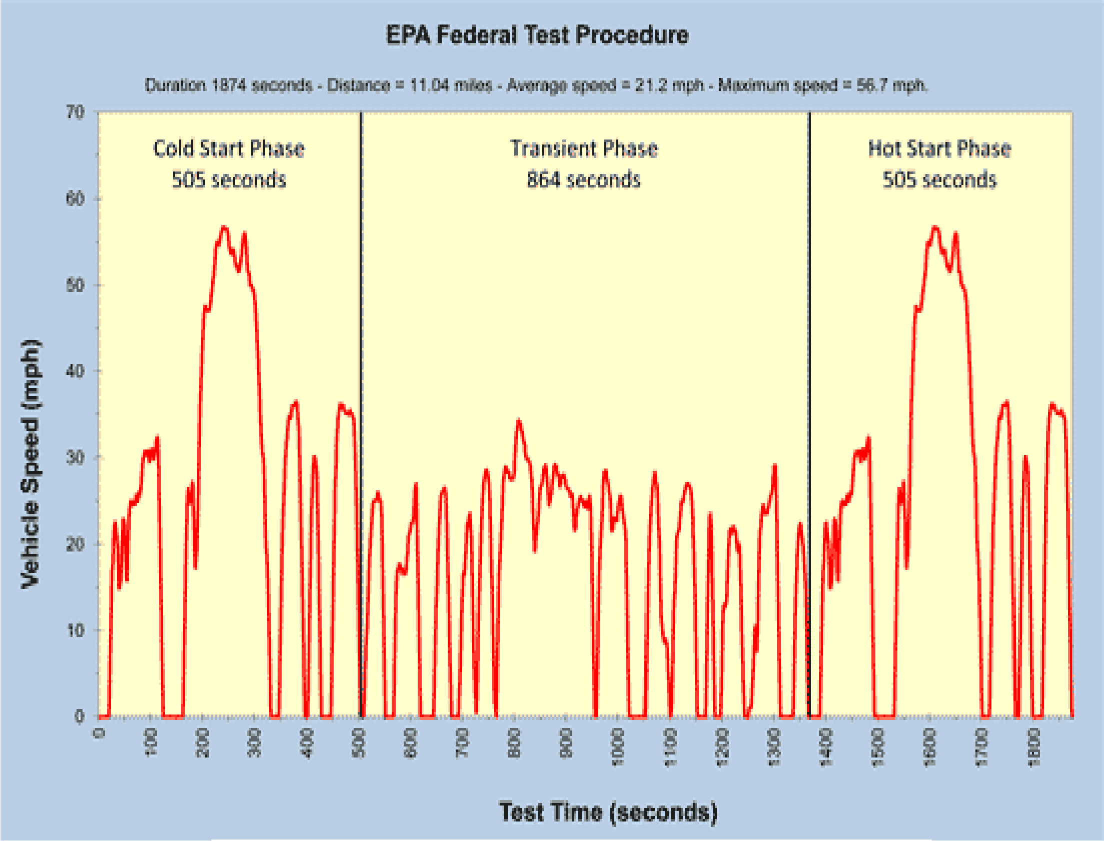
- Points below 10 bar/deg. MPRR limit
- Double DI injection, 60-80% PFI ratio, no EGR, 1.2-1.3 bar intake pressure
- BTE ~ 34-36%, from 10-22 kW (32 kW ~ 40% BTE, future operating point)
- 300>EGT>200 deg. C, for catalyst light-off

FTP75 drive cycle

"Represents urban driving, in which a vehicle is started with the engine cold and driven in stop-and-go rush hour traffic"

Start with engine cold, we started with warm engine

Includes a 600 second cold soak period after 1369 seconds



http://fueleconomy.gov/feg/fe_test_schedules.shtml

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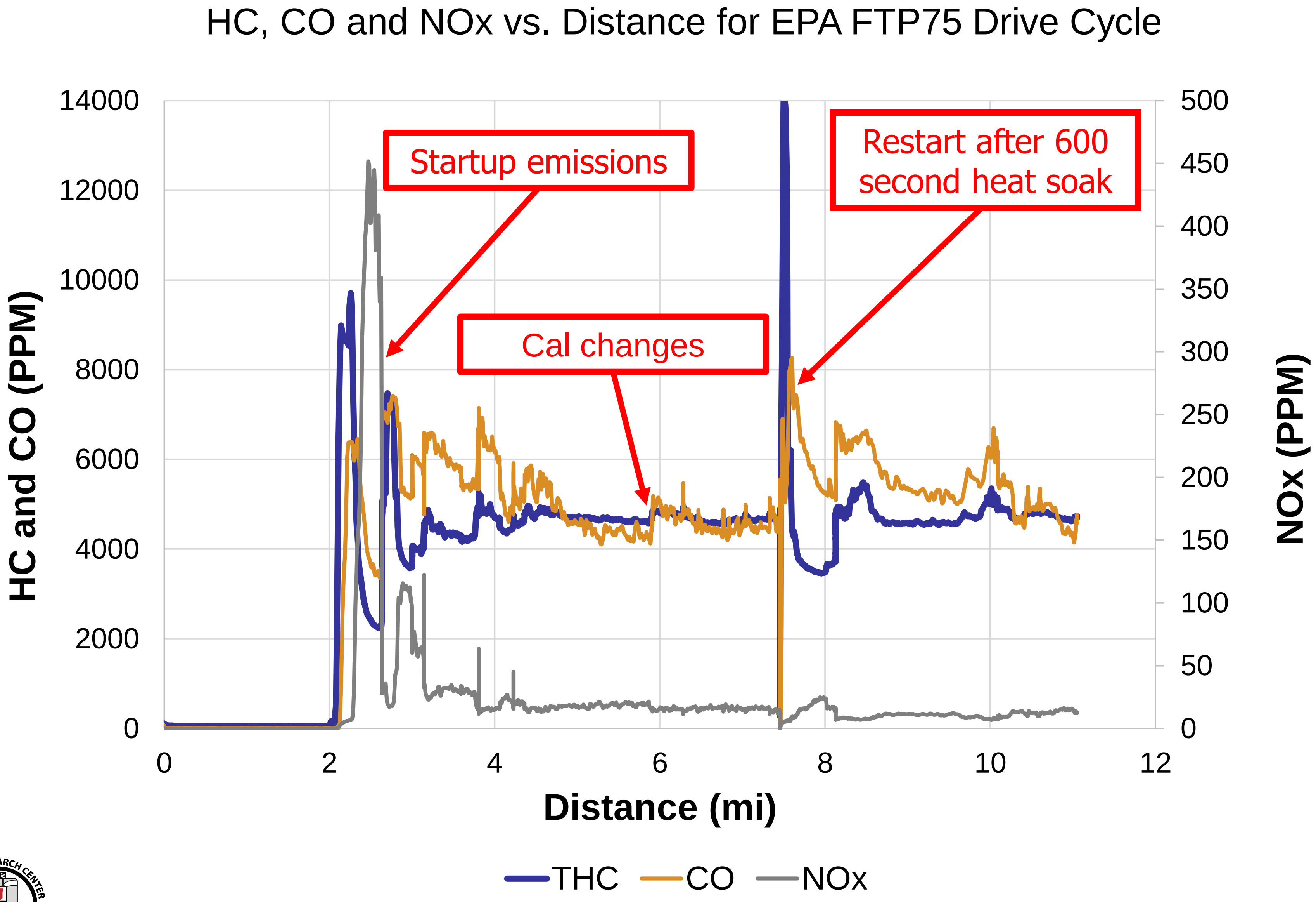
FTP75 drive cycle

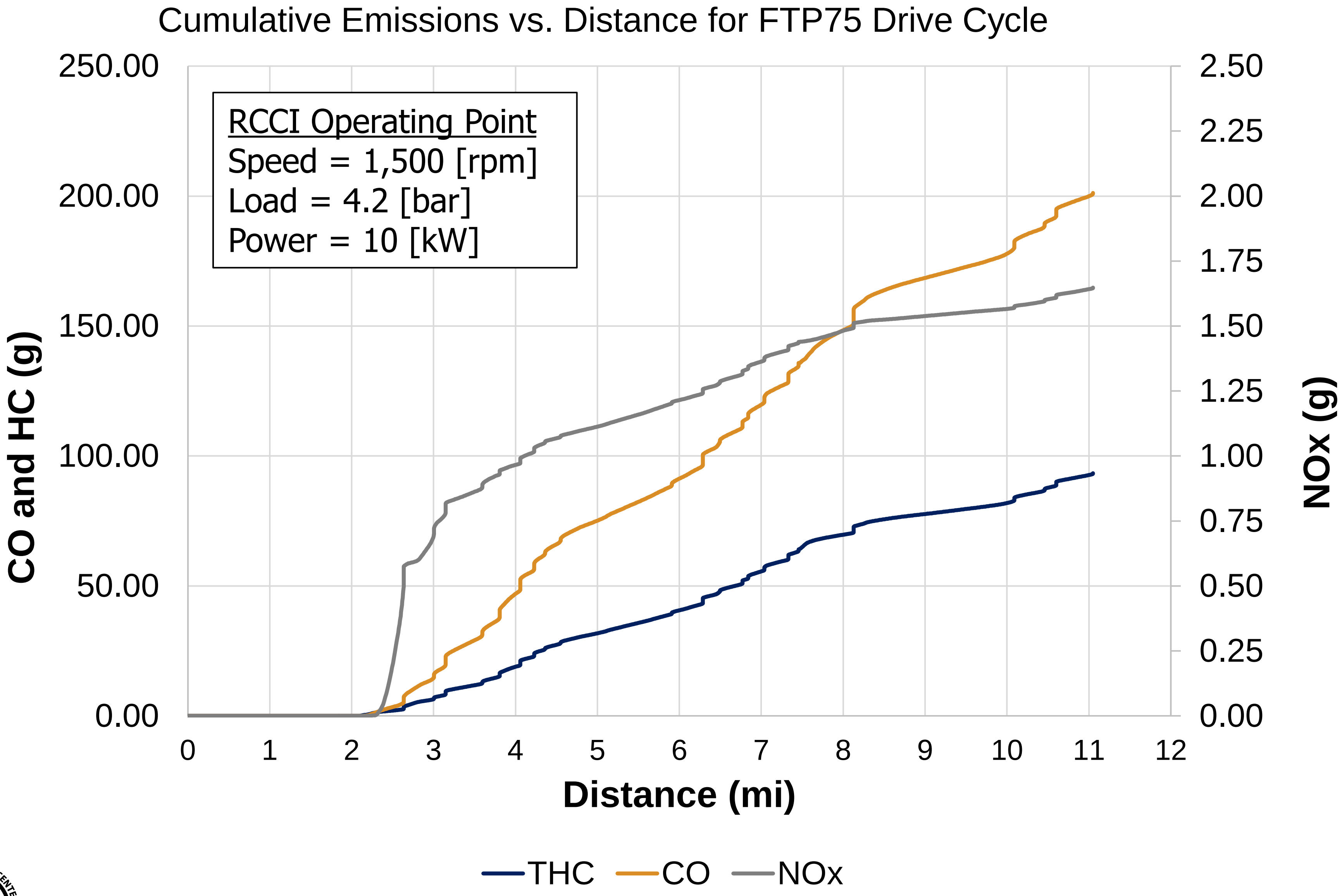


Startup emissions

Cal changes

Restart after 600 second heat soak

FTP75 drive cycle



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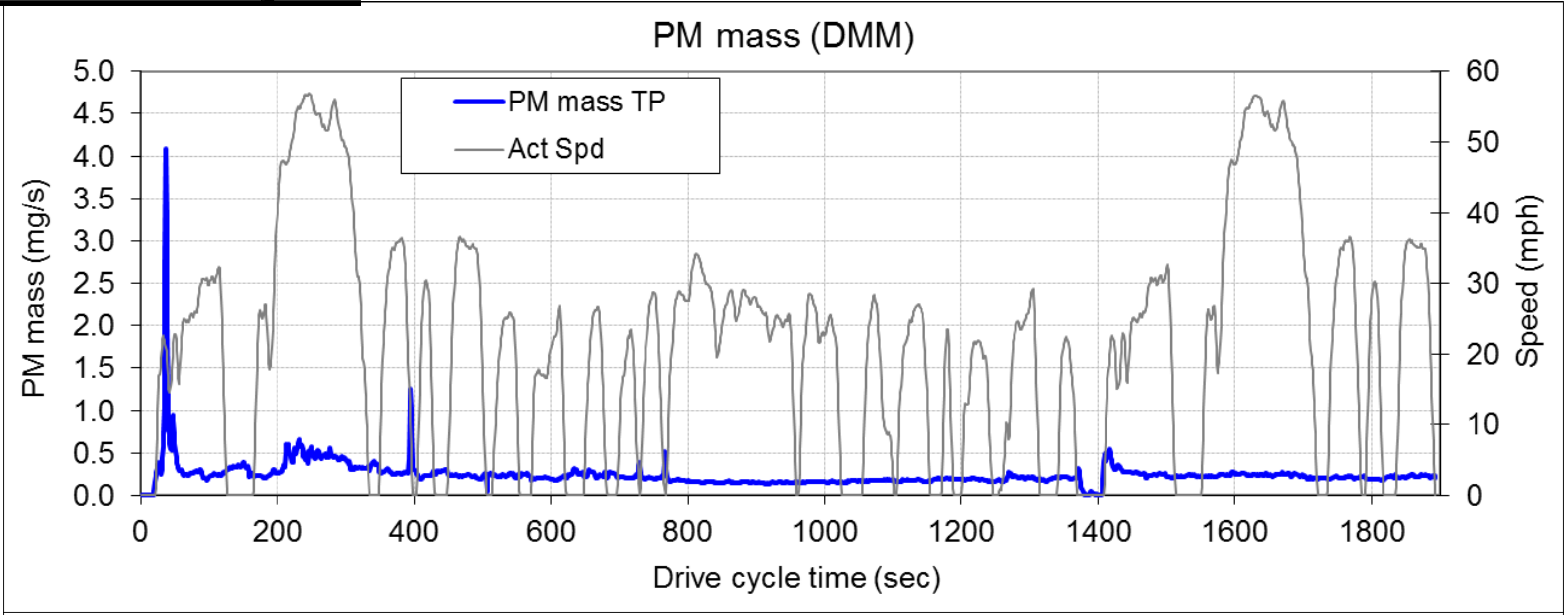
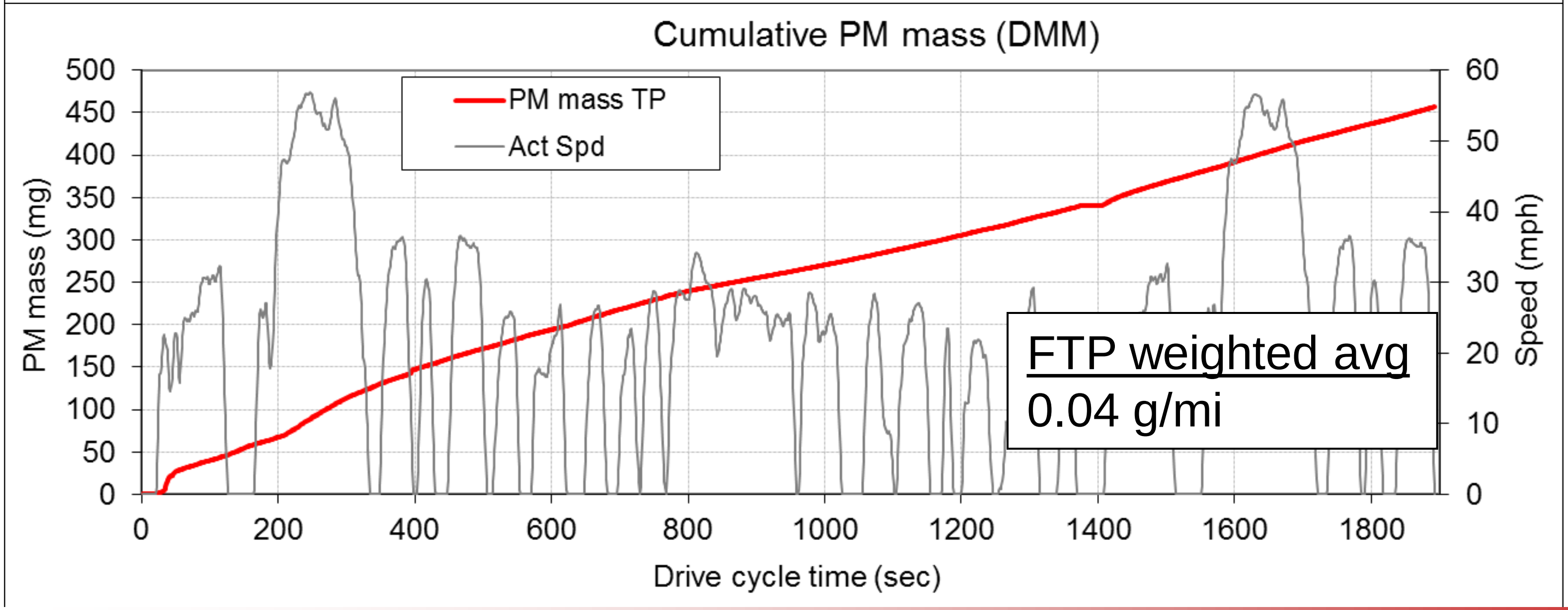
FTP75 drive cycle





FTP weighted avg
0.04 g/mi

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FTP75 drive cycle

UW w/10 kW	w/20 kW	20 kW w/Cat	Cat w/EGR	EGR w/cal	Volt BL	g/mile
8.45	5.400	0.081	0.065	0.052	0.0577	HC
18.21	8.737	0.131	0.105	0.084	1.2435	CO
0.149	0.159	0.159	0.127	0.064	0.0219	NOx
0.041	0.022	0.011	0.009	0.009	-	PM

Assumptions: engine on-time 554 sec, Eta_cat=0.985, EGR=20%, PM reduced 50%, Calibration improvements of 20% HC/CO and 50% NOx, no additional startup emissions

Nearly charge sustaining (+1.5% SOC), 8.9 kW used
Total Energy (Drive motor and 12v system) = 3,725 W-hr
Average Energy = 335 W-hr/mi

Charge Sustaining Fuel Efficiency

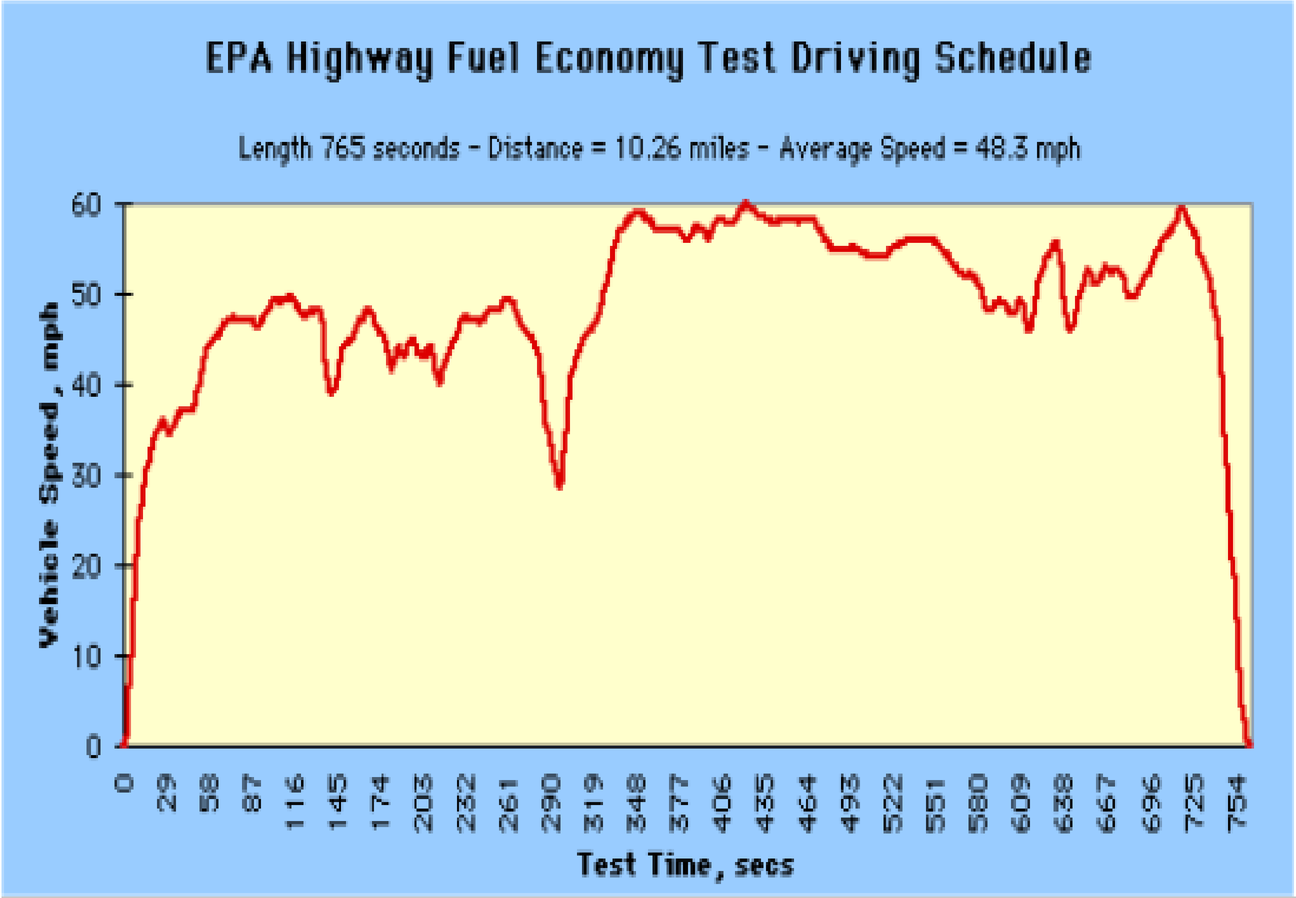
UW w/10 kW	w/20 kW	w/30kW	Volt BL	
34 +/- 2	46.5 +/-3	48.4 +/-3	45	MPG

Assumptions: logged HV battery kW, 35% BTE, 70% PFI and pump fuel properties

Volt fuel economy data from ANL Downloadable Dynamometer Database (http://www.transportation.anl.gov/D3/), emissions data from EPA http://www.epa.gov/otaq/tcldata.htm

EPA highway fuel economy test

“Represents a mixture of rural and Interstate highway driving with a warmed-up engine, typical of longer trips in free-flowing traffic.”



http://fueleconomy.gov/feg/fe_test_schedules.shtml

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HWFET Test

w/15 kW	w/20 kW	20 kW w/Cat	Cat w/EGR	EGR w/cal	Volt BL	g/mile
6.14	3.893	0.058	0.047	0.037	0.0102	HC
10.39	6.587	0.099	0.079	0.063	0.44	CO
0.098	0.062	0.062	0.050	0.035	0.0049	NOx
0.033	0.021	0.01	0.008	0.008	-	PM

Assumptions: engine on-time 485 sec, Eta_cat=0.985, EGR=20%, PM reduced 50%, Calibration improvements of 20% HC/CO and 50% NOx, no additional startup emissions

Charge sustaining (net 0% SOC), 14.8 kW used
Total Energy (Drive motor and 12V system) = 2,967 W-hr
Average Energy = 288 W-hr/mi

Charge Sustaining Fuel Efficiency

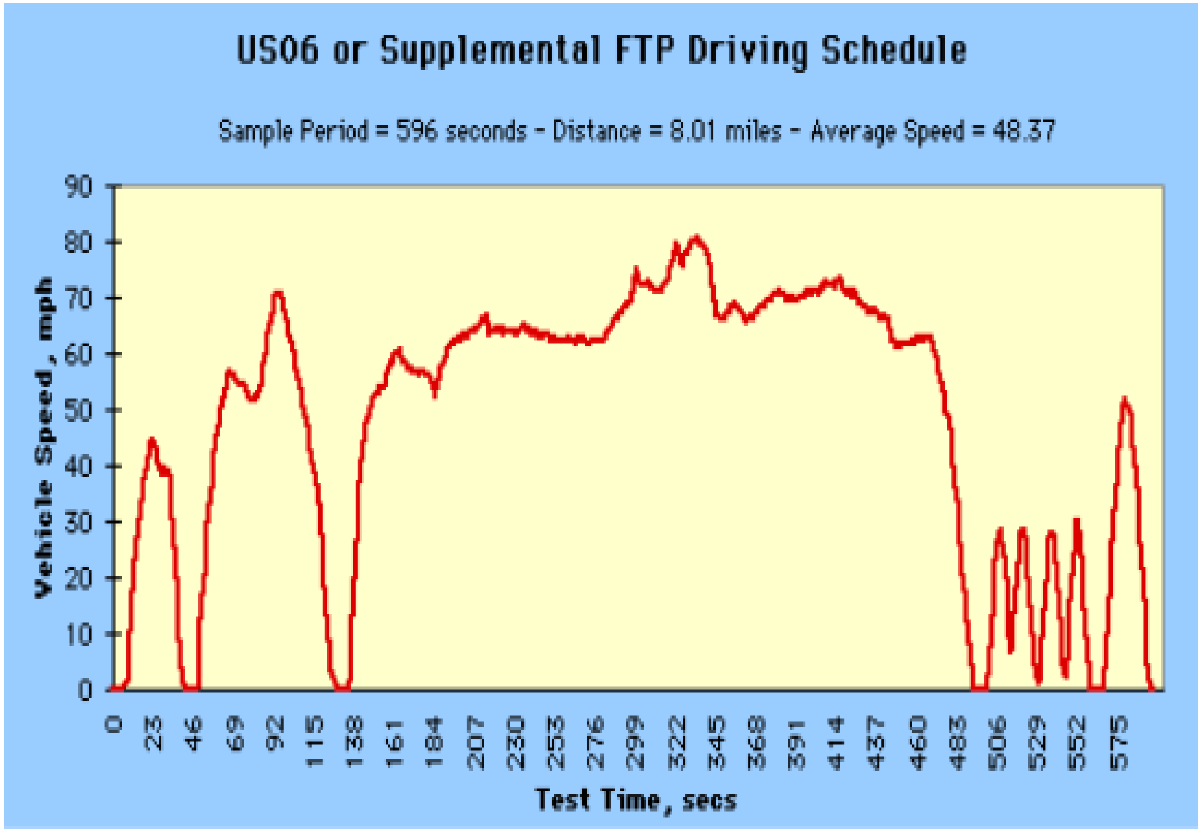
UW w/15 kW	w/20 kW	w/30kW	Volt BL	
40 +/- 2	49.3 +/-3	51.4 +/-3	48	MPG

Assumptions: logged HV battery kW, 35% BTE, 70% PFI and pump fuel properties

US06 test

"Represents city and highway driving at higher speeds with more aggressive acceleration and braking." Speeds in excess of 80 mph

Harshest acceleration and decelerations: 8.46 mph/sec maximum acceleration



http://fueleconomy.gov/feg/fe_test_schedules.shtml

Spannbauer, 2014

US06 test

w/20 kW	20 kW w/Cat	Cat w/EGR	EGR w/cal	Volt BL	g/mile
8.11	0.122	0.097	0.078	0.011	HC
13.12	0.197	0.157	0.126	1.789	CO
0.239	0.239	0.191	0.096	0.008	NOx
-	-	-	-	-	PM

Assumptions: Eta_cat=0.985, EGR=20%, PM reduced 50%, Calibration improvements of 20% HC/CO and 50% NOx, no additional startup emissions

Battery charge not sustained (-6% SOC), 18.63 kW engine power + 5.11 kW of electricity used
Total Energy (Drive motor and 12V system) = 3,586 W-hr
Average Energy = 446 W-hr/mi

Charge Sustaining Fuel Efficiency

UW w/20 kW	w/30kW	Volt BL	
27 +/-2	31 +/-2	32.5	MPG

Assumptions: logged HV battery kW, subtracted 6% SOC fuel, 35% BTE, 70% PFI and pump fuel properties

Spannbauer, 2014

UW RCCI vehicle test summary

1. **Successfully installed UW designed 2nd generation RCCI pistons and RCCI engine into a series hybrid vehicle**
2. **Operated an RCCI powered vehicle at 3 different power levels over 3 different Federal Test Cycles**
3. **Preliminary results encouraging - First test with new piston geometry, Engine not broken in before testing, No dyno or CFD testing for calibration reference, only previous MCE tests**
4. **Saw similar engine-out emissions as previous laboratory tests**
   - Far from optimal engine calibrations
5. **Fuel economy comparable to Chevy Volt**
   - No regenerative braking, rough RCCI calibration, etc.
6. **Future tests planned at ORNL in late April 2014**
   - Same test points but using updated operating strategy (regenerative braking, EGR, calibration, etc.) and hardware (i.e., DOC/DPF, etc.)

RCCI summary

Advanced engine combustion strategies such as RCCI show promise for fuel efficiency and emissions improvements

RCCI shown in single- and multi-cylinder engine, plus vehicle tests to yield clean, quiet, and efficient combustion over wide load/speed range

- HD: EPA 2010 NOx/PM emissions met in-cylinder with peak GIE >55%
- LD: Low NOx and PM emissions with less EGR needed over FTP cycle

Multi-mode LD RCCI strategy uses optimized high EGR diesel combustion at low load (idle) and then no EGR up to Mode 5 (~9 bar IMEP)

RCCI LD modeling indicates ~8% improvement in fuel consumption over CDC+SCR over FTP cycle using same engine and conditions.

RCCI meets Tier 2 bin 5 without need for NOx after-treatment or DPF, but DOC will likely be needed for UHC reduction

Modeling indicates that further RCCI optimization requires:

higher boost pressure, higher piston temps, reduced swirl, reduced surface area

steel piston, optimized crevice design

Future experiments/modeling in HD and LD engines will continue to explore RCCI with optimized pistons and alternative fuels.

RCCI
Reactivity Controlled Compression Ignition

Future of IC engines - new directions

New technologies are needed to improve efficiency of gasoline and diesels. Engines need to be optimized to balance emissions, fuel cost, and market competitiveness.

Advanced CFD models and optimization methods increasingly used by the industry.
- made possible by dramatic increases in computer speeds (x10^4 in last 15 years)
- significantly reduces requirements for expensive experimental testing

Development of predictive models for engine physical processes has been an additional enabling factor for advanced concepts in engine design
- CFD tools are mature enough to guide the development of more efficient and cleaner internal combustion engines.

New low temperature combustion (LTC) concepts, such as:

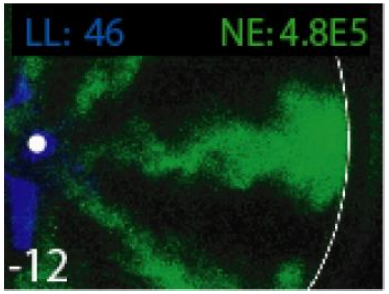
Homogeneous Charge Compression Ignition (HCCI),
Premixed Charge Compression Ignition (PCCI) and
Reactivity Controlled Compression Ignition (RCCI), …….

offer promise of dramatically improved engine efficiencies
- can be explored/optimized with CFD tools.

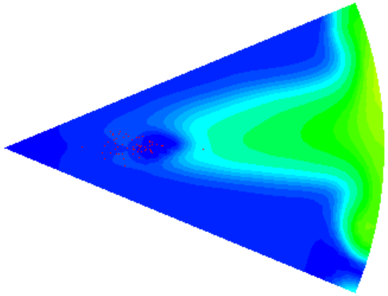
Hu, 2007

Future of engine CFD modeling

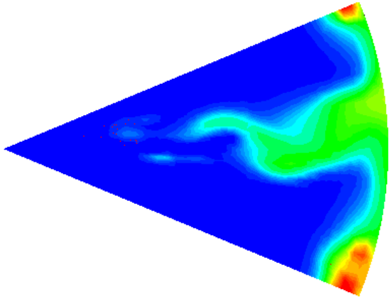
Incrementally improved models, used for engine design with less engine testing.



Experiment



RANS CHEMKIN

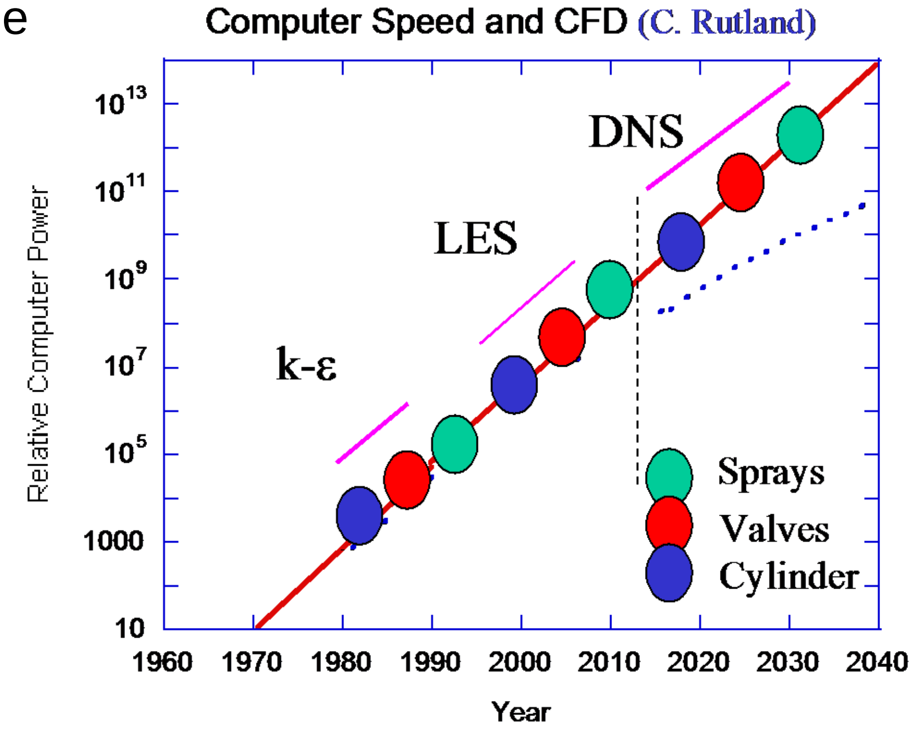


LES CHEMKIN

Models are a storehouse of current knowledge

Engine CFD Timeline

(1960's) - no local resolution
(1970-80's) - 1&2-D
physics sub-grid scale
(1990's) - 3D 1-mm grids
subgrid scale models
(2000's) - all relevant gas-phase
scales resolved
(2020's) - all liquid and gas
scales resolved
+ Detailed kinetics + nozzle processes



Computer Speed and CFD (C. Rutland)

Abbott, 2010

The long term future:

How Do We Supply the World’s Energy Needs?

Derek Abbott, University of Adelaide, Australia

“ABSTRACT

We take a fresh look at the major nonrenewable and renewable energy sources and examine their long-term viability, scalability, and the sustainability of the resources that they use.

We achieve this by asking what would happen if each energy source was a single supply of power for the world, as a gedanken experiment.

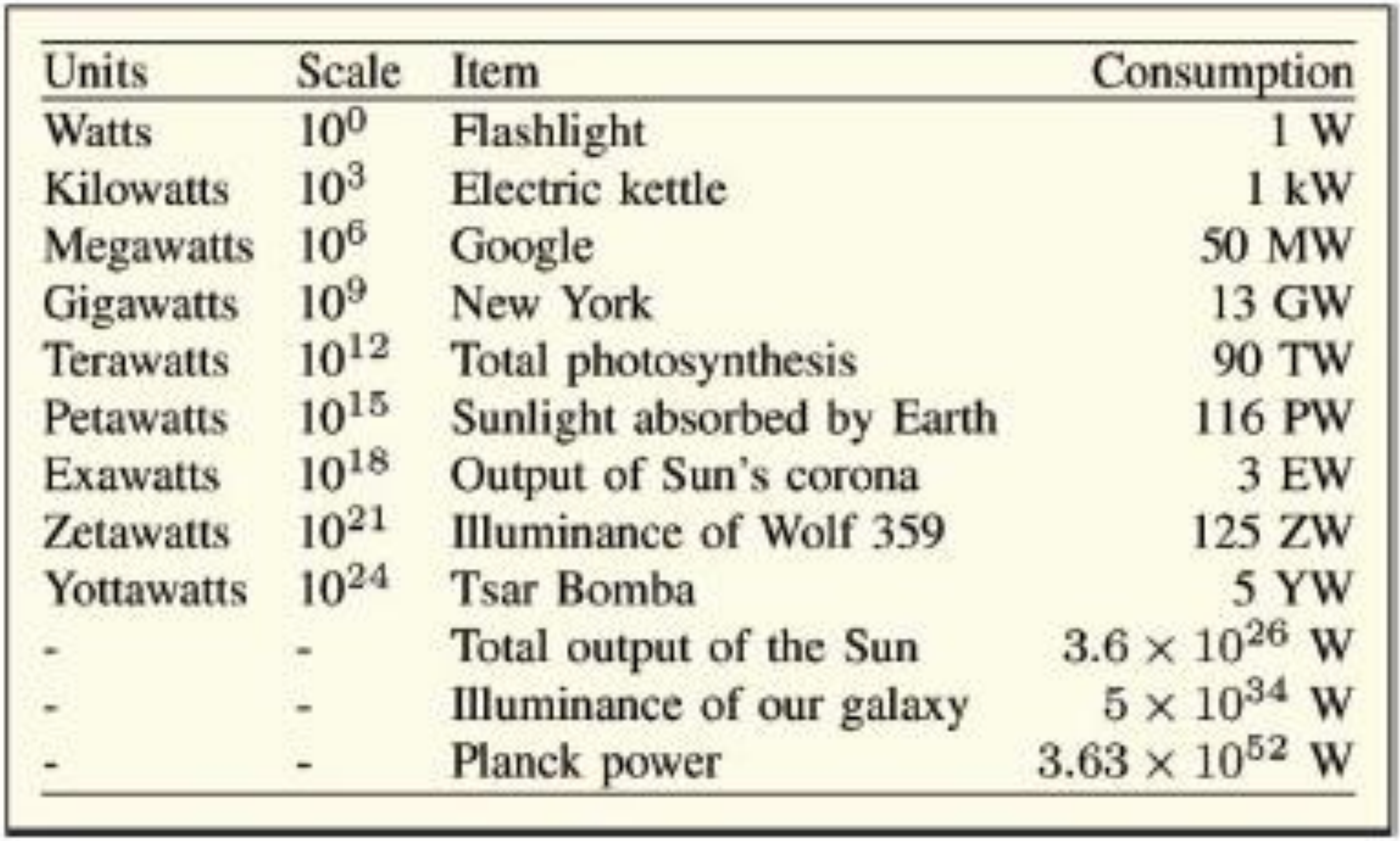
From this perspective, a solar hydrogen economy emerges as a dominant solution to the world’s energy needs.”

Abbott, 2010

How much energy do we use? - 15 TeraWatts

We use the equivalent energy of every person on earth (6 billion) running 25, 100 W light bulbs.

Table 1 Orders of Magnitude for Power in Watts



Units	Scale	Item	Consumption
Watts	10^0	Flashlight	1 W
Kilowatts	10^3	Electric kettle	1 kW
Megawatts	10^6	Google	50 MW
Gigawatts	10^9	New York	13 GW
Terawatts	10^{12}	Total photosynthesis	90 TW
Petawatts	10^{15}	Sunlight absorbed by Earth	116 PW
Exawatts	10^{18}	Output of Sun's corona	3 EW
Zetawatts	10^{21}	Illuminance of Wolf 359	125 ZW
Yottawatts	10^{24}	Tsar Bomba	5 YW
-	-	Total output of the Sun	3.6×10^{26} W
-	-	Illuminance of our galaxy	5×10^{34} W
-	-	Planck power	3.63×10^{52} W

Abbott, 2010

How to supply world’s 15 TeraWatt energy needs?

At current rates, to supply the world’s energy use, we have enough:

uranium for nuclear for 5 years,
fossil oil for 42 years,
natural gas 60 years,
and coal for 130 years.

But, centuries from now we will still need fuels to make fertilizers, plastics and to lubricate machinery,

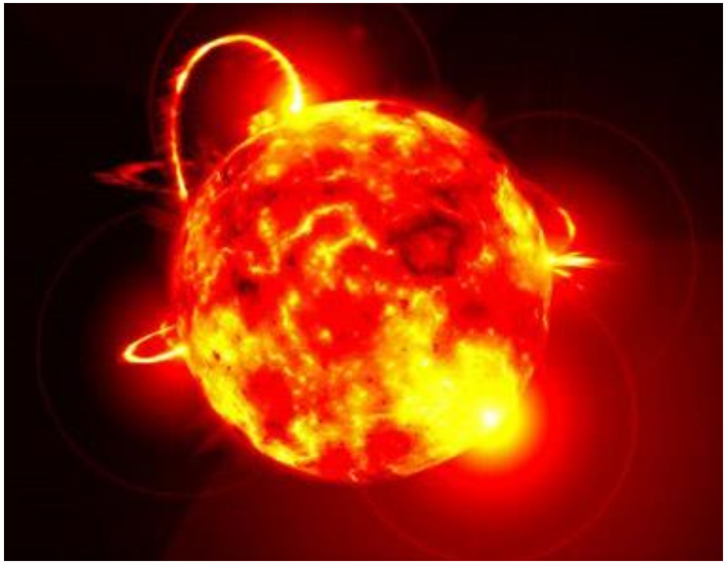
And a billion years from now when sun turns into a red giant, we will probably need nuclear so some of us can escape to a new solar system.

Abbott, 2010

Non-sustainability

Assume 5 billion people drive a car with a 50 kW engine for 1 hour per day
→ 10 TJ consumed in world each second
i.e., 10 TW: 2/3 current world energy consumption.

Abbott's point is that we cannot afford to recklessly deplete precious non-renewable sources of energy for man's continued survival on earth.



Abbott considers fossil, nuclear, wind, hydroelectric, wave, geothermal energy sources and concludes that the only sustainable long term energy scenario is a Solar Hydrogen Economy.

(wind, hydroelectric, wave come from the sun anyway, and the sun is a fusion reactor!)

Part 10: Vehicle Applications, Future of IC Engines

Abbott, 2010

Solar energy incident on the earth in one month is more than all the energy in the world’s fuel resources combined.

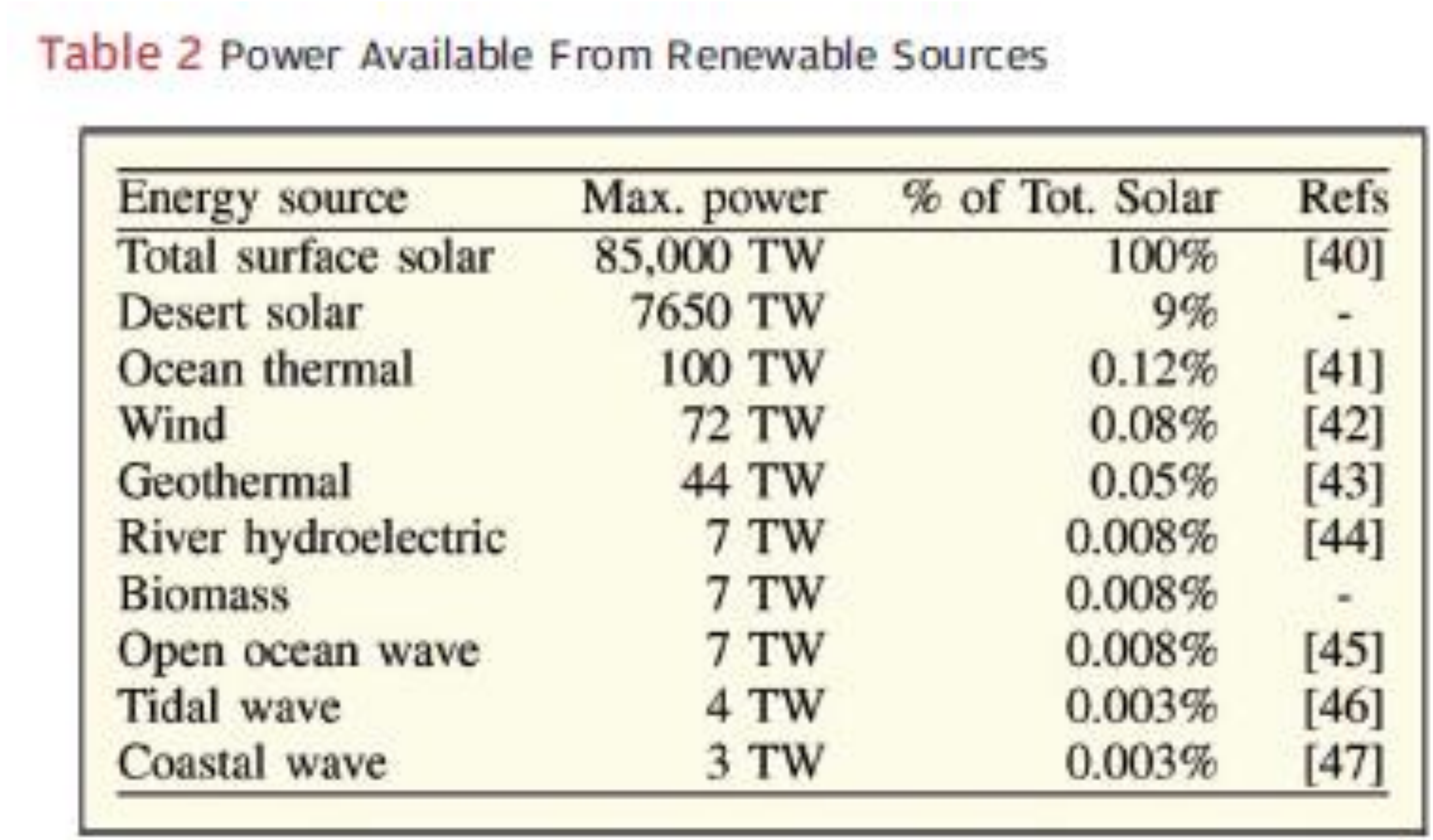


Table 2 Power Available From Renewable Sources

Energy source	Max. power	% of Tot. Solar	Refs
Total surface solar	85,000 TW	100%	[40]
Desert solar	7650 TW	9%	-
Ocean thermal	100 TW	0.12%	[41]
Wind	72 TW	0.08%	[42]
Geothermal	44 TW	0.05%	[43]
River hydroelectric	7 TW	0.008%	[44]
Biomass	7 TW	0.008%	-
Open ocean wave	7 TW	0.008%	[45]
Tidal wave	4 TW	0.003%	[46]
Coastal wave	3 TW	0.003%	[47]

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Large amount of energy from the sun!

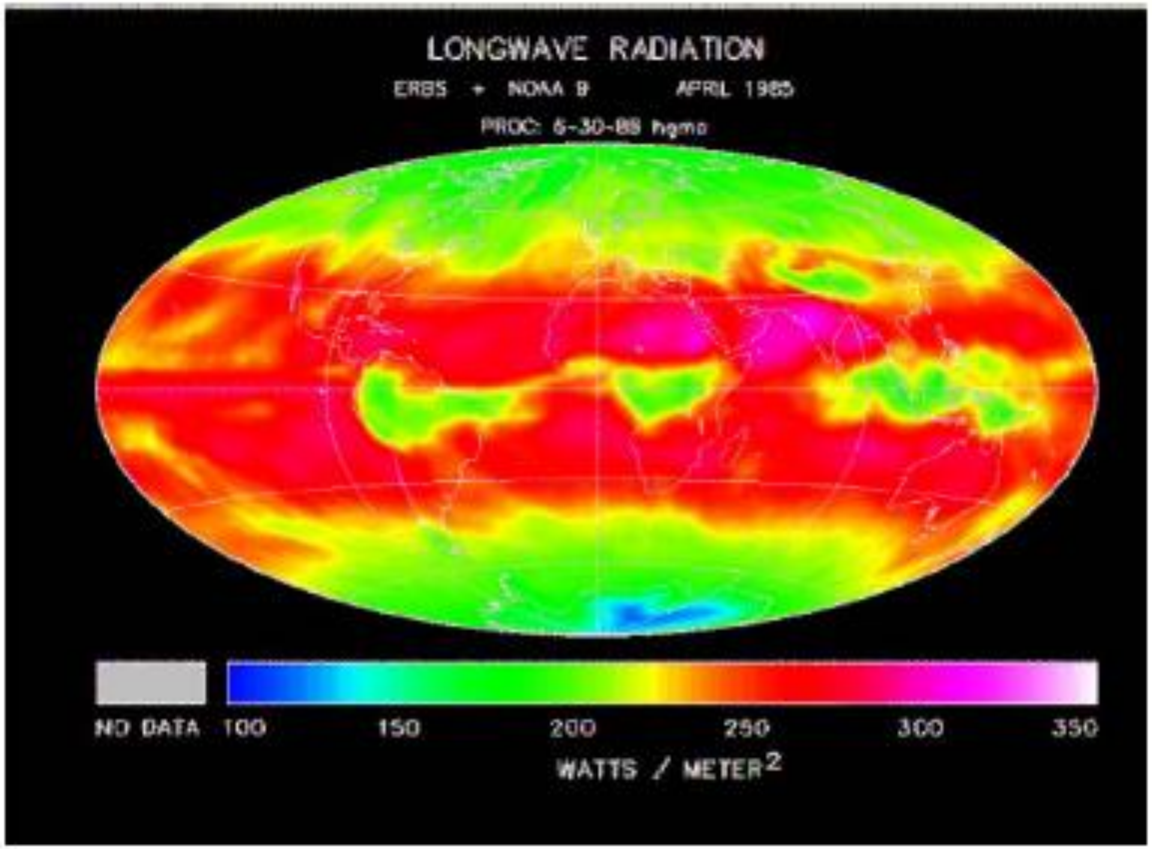

Fig. 2. *This Erbe satellite image clearly identifies the strategic regions for solar collector farms. Actual insolation (solar power per unit area) levels are not obtained from this image, but it can be used to estimate which regions are relatively hotter. Note that in the hottest regions insolation levels can exceed 1 kW/m^2.*

Usable Solar Power incident on earth is 5,000 times our global energy consumption.

Deserts are 9% of world's surface area

If we tap sunlight on 1% of earth's surface at conversion efficiency of 1%, we can meet current world energy demand.

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Solar collection – proven technology!

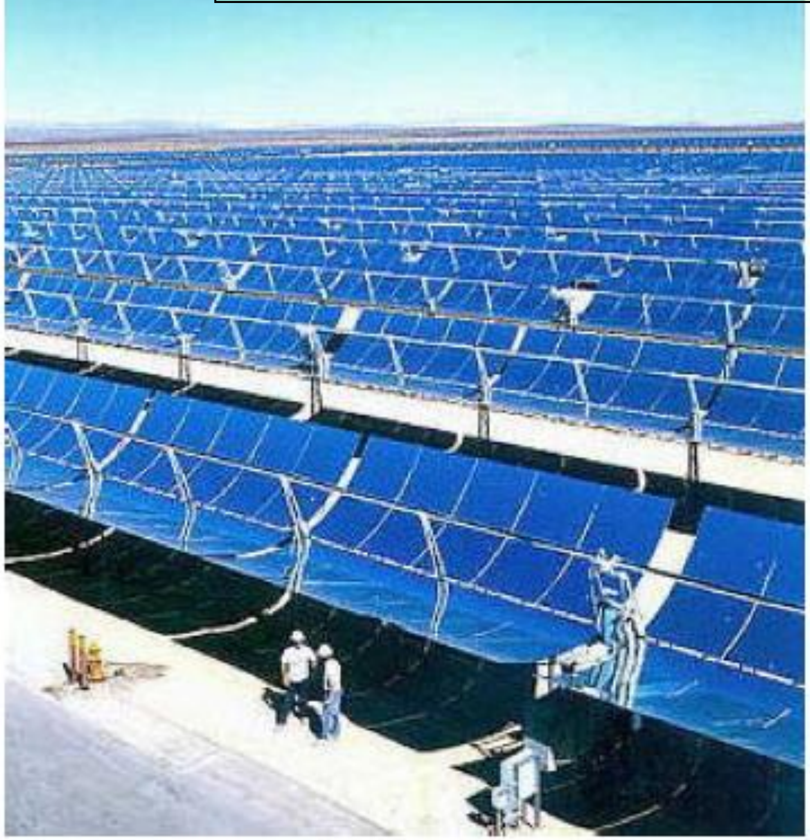

Fig. 3. *The Solar Energy Generating Systems (SEGS) solar trough farm at Kramer Junction, California. The concept is that the reflective troughs focus sunlight on a pipe containing oil in a closed-cycle, which heats water to create steam to turbines. In total there are nine SEGS farms, with two at Dagett, five at Kramer Junction, and two at Harper Lake; all in California's Mojave Desert. The total area occupied is 2.4 sq km, generating 354 MW of power. These figures scale up to a footprint of 320 km by 320 km, if we were to supply 15 TW with this method. The nine plants have gradually been installed from 1984 to 1990, demonstrating over 20 years of performance without malfunction. Source: Power Corp.*

Fig. 4. *The Stirling Energy Systems (SES) SunCatcher solar dish farm being developed in California. Each 11.6 m (38 ft) diameter dish automatically tracks the sun and powers a 25 kW Stirling cycle generator. Source: Stirling Energy Systems.*

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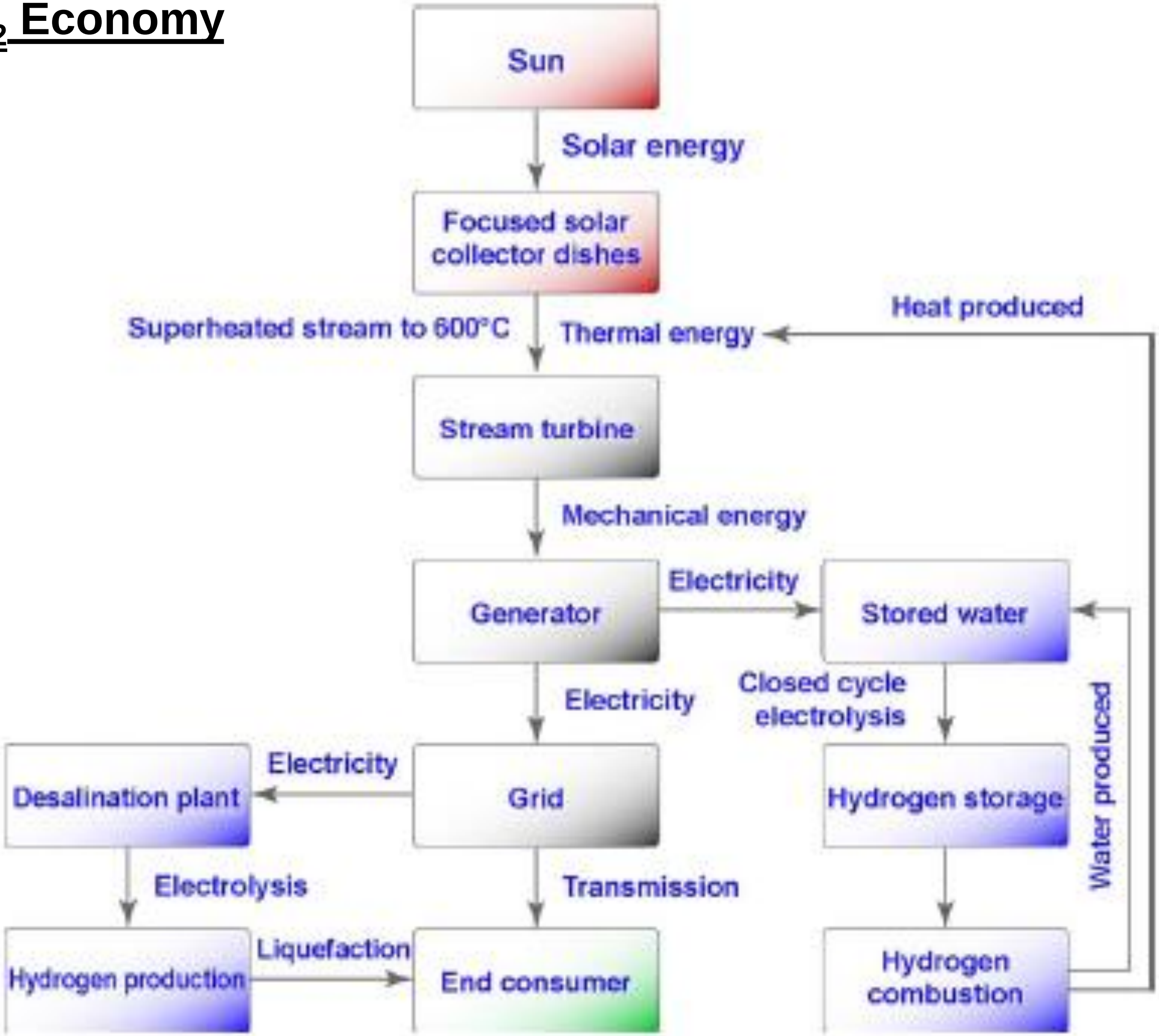
Solar H_2 Economy



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H_2 for transportation – infrastructure?

60 million vehicles/year:

For battery electric we have enough lithium on earth for only 23 years

Fuel cells require exotic rare Materials

IC engine is sustainable
(available materials)

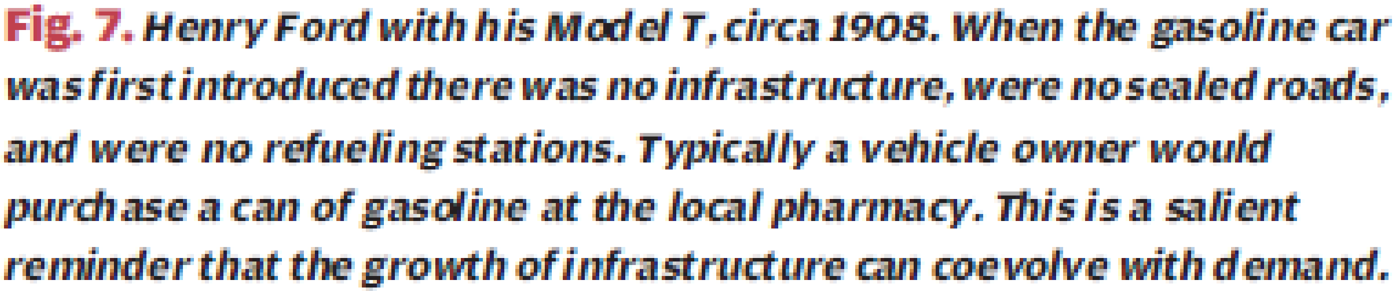

Fig. 7. *Henry Ford with his Model T, circa 1908. When the gasoline car was first introduced there was no infrastructure, were no sealed roads, and were no refueling stations. Typically a vehicle owner would purchase a can of gasoline at the local pharmacy. This is a salient reminder that the growth of infrastructure can coevolve with demand.*

Liquid hydrogen & hydrogen gas engines

BMW Hydrogen 7 (2006)
260 HP twelve-cylinder engine

17.6 lb of liquid H_2 storage tank,
cruising range 125 miles, 0-62.1 mph in 9.5s

Ford E-450 (2008)

Mazda H_2 Rotary RX-8 (2008)

IC engine: transportation powerplant
- field of engine research will be alive for next billion or so years!

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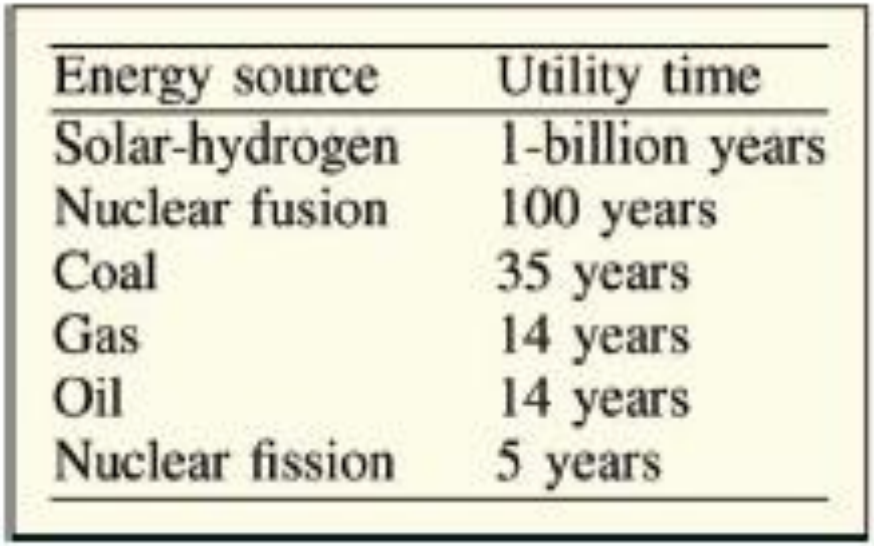
Solar hydrogen economy

- reversible, sustainable future
- with unlimited energy supply!

Table 3 Consolidated Utility Time (CUT)



Energy source	Utility time
Solar-hydrogen	1-billion years
Nuclear fusion	100 years
Coal	35 years
Gas	14 years
Oil	14 years
Nuclear fission	5 years

Closure

Availability of cheap energy has led to distorted world economies/priorities

Next 30-40 years will require major innovations in IC engines

- dwindling resources and minimized environmental impact
- current energy usage rates are clearly unsustainable.

Many energy “solutions” (battery, fuel cell, nuclear) are only short term and resources are better saved for future generations

The only really long-term sustainable energy source is solar hydrogen

Research will be needed to improve efficiency of electricity generation, H_2 production/storage and engine efficiency

The switch to the H_2 economy will take considerable time and effort

Until this occurs, research on more efficient usage of fossil and other fuels is urgently needed!

> “I’d put my money on the sun and solar energy.   What a source of power!
> I hope we don’t have to wait until oil and coal run out before we tackle that.”
> Thomas Edison (1931) in conversation with Henry Ford and Harvey Firestone.