Developments in SI Engines for Light Duty Vehicles including Hybrid Powertrains

October 25th, 2011

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Intro

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- **Spark-ignition engines** are by far the **dominant powertrain** choice for light-duty vehicles in the US.

WHY AND WILL THIS BE CHANGING?

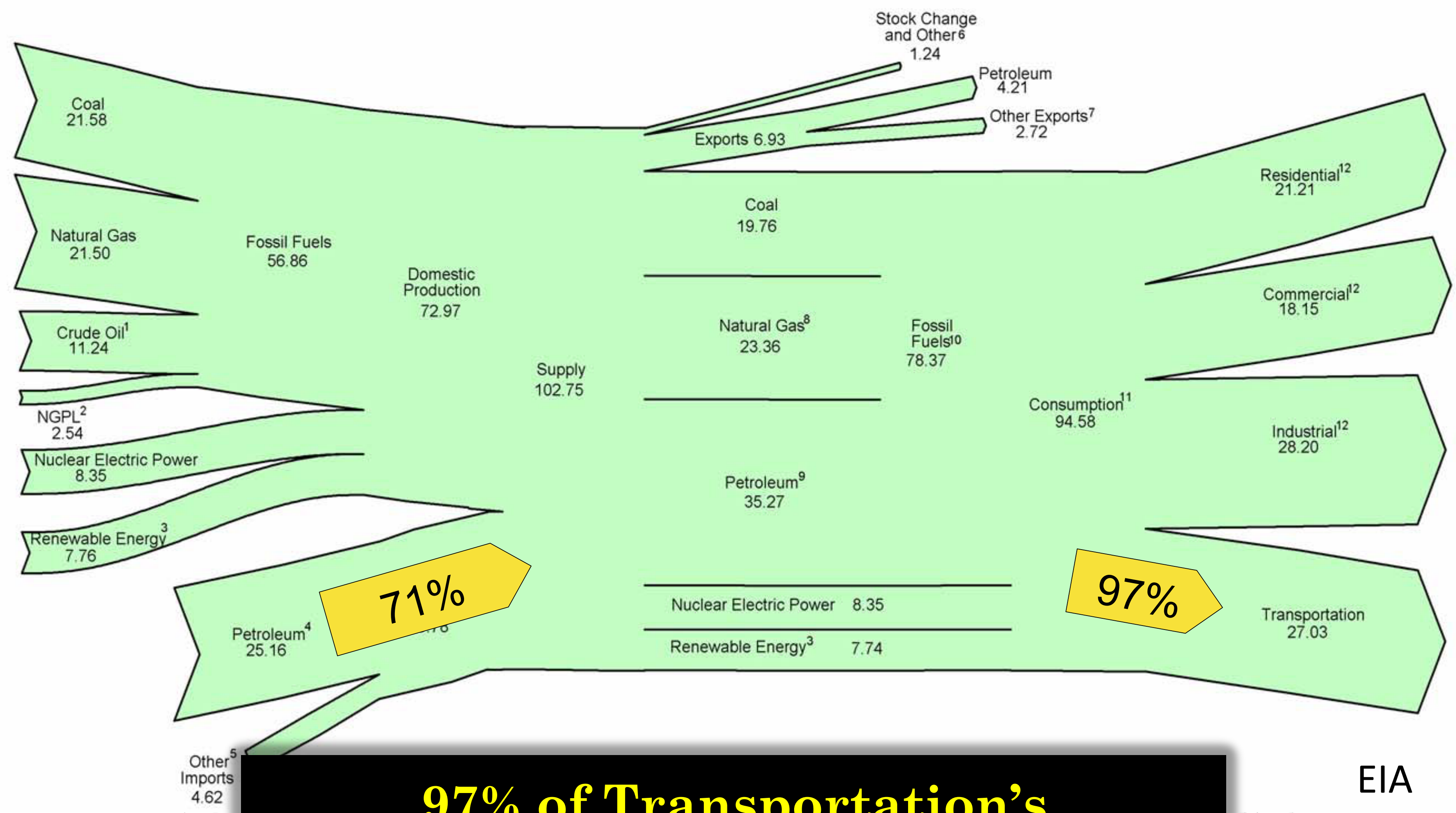
- **Requirements and regulations** in the US for **emissions** and **fuel consumption** will be examined in context of **technology cost** and return on investment.
- **Advanced SI engine technologies** including direct injection, air-charge, boosting, advanced combustion, and controls will also be discussed.-

Michigan Tech

Student Enrollment 7200
83% in STEM

Where are we and where are we headed?

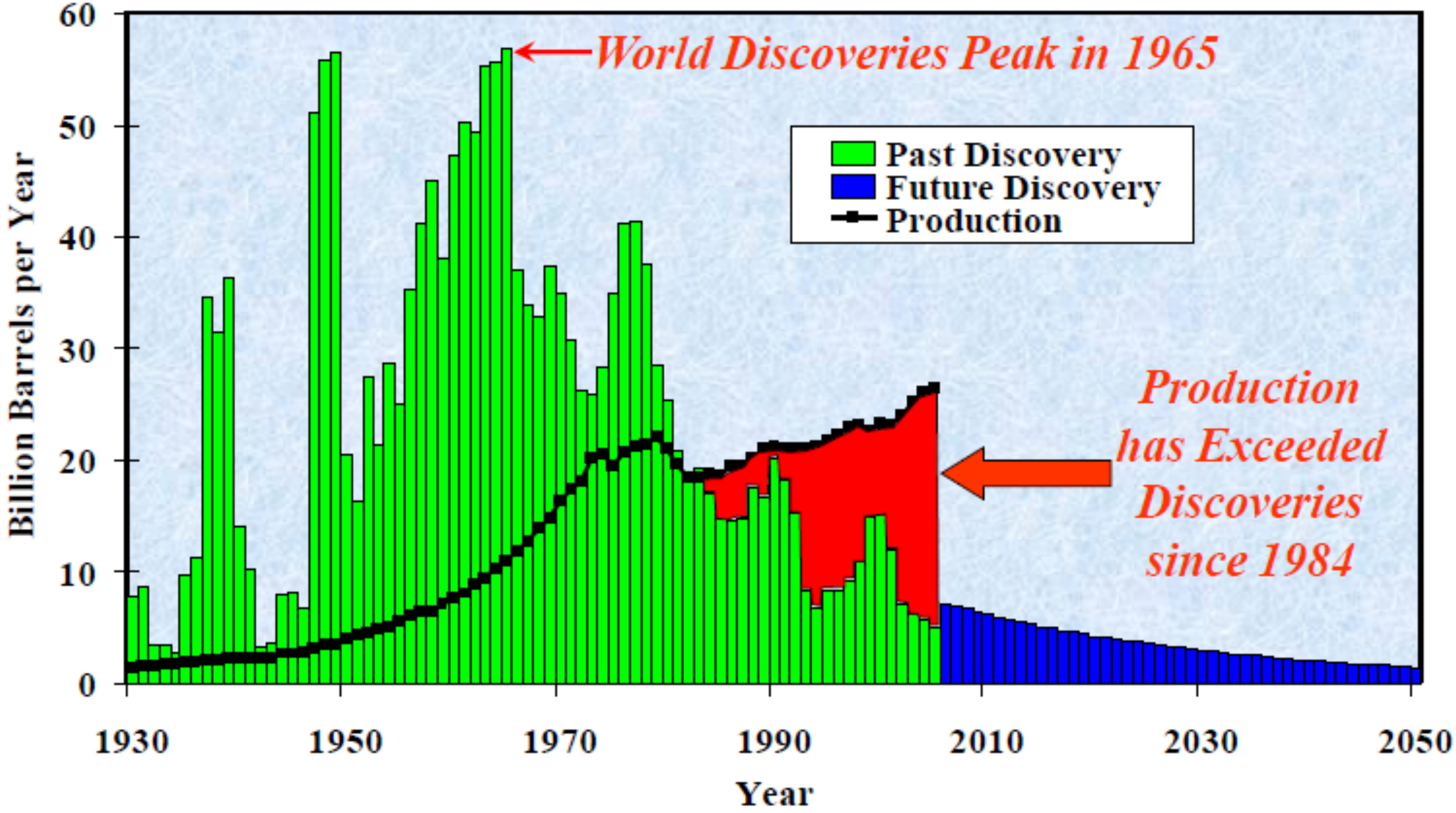
ENERGY



97% of Transportation's Energy comes from Fossil Fuels

EIA 2009

The Growing Gap between Production and Discovery of Regular Conventional Oil (1930-2050)

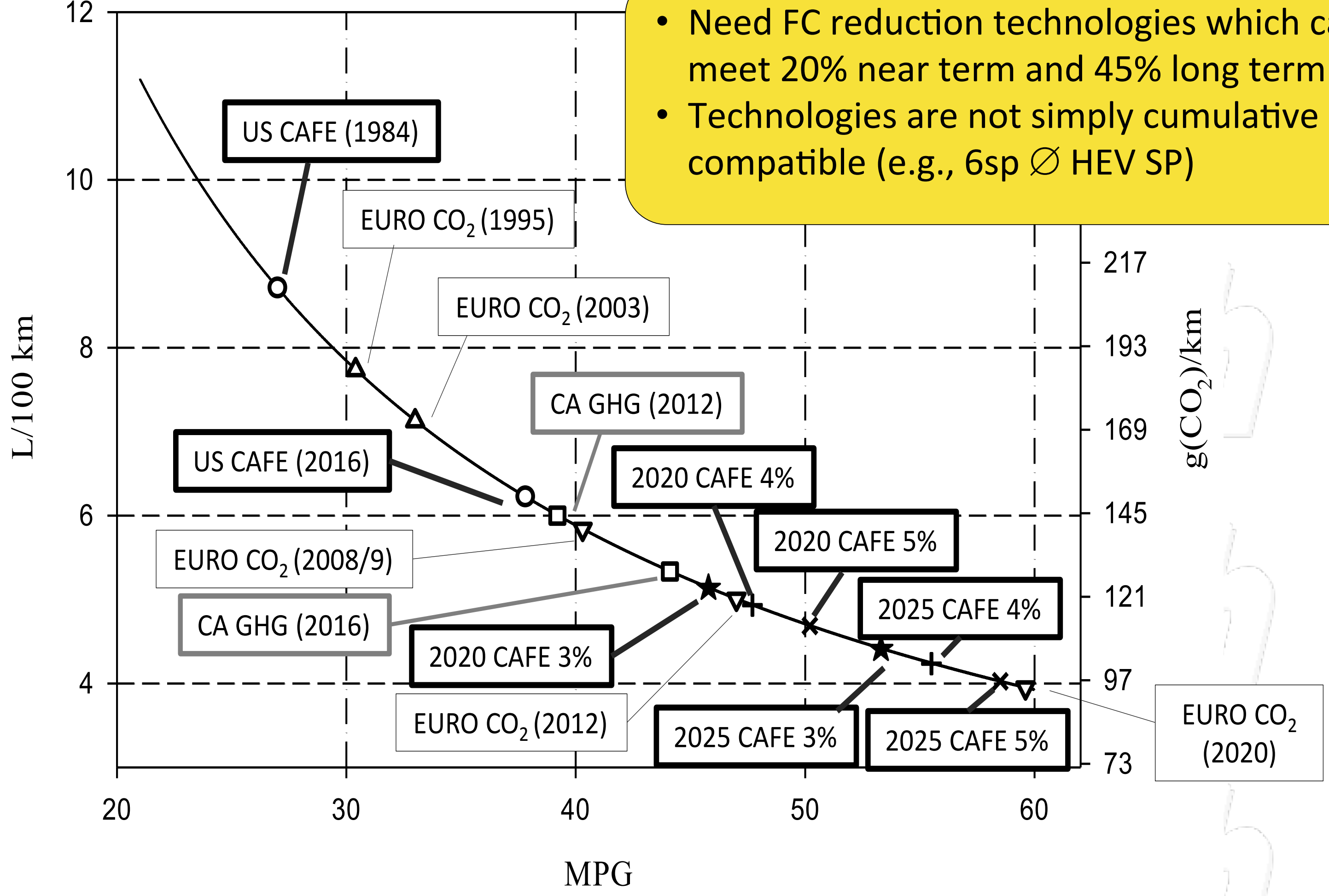


Past discoveries have been backdated with revisions from ExxonMobil (2002) to reflect "Reserve Growth"

(from Campbell, personal communication, September, 2006)

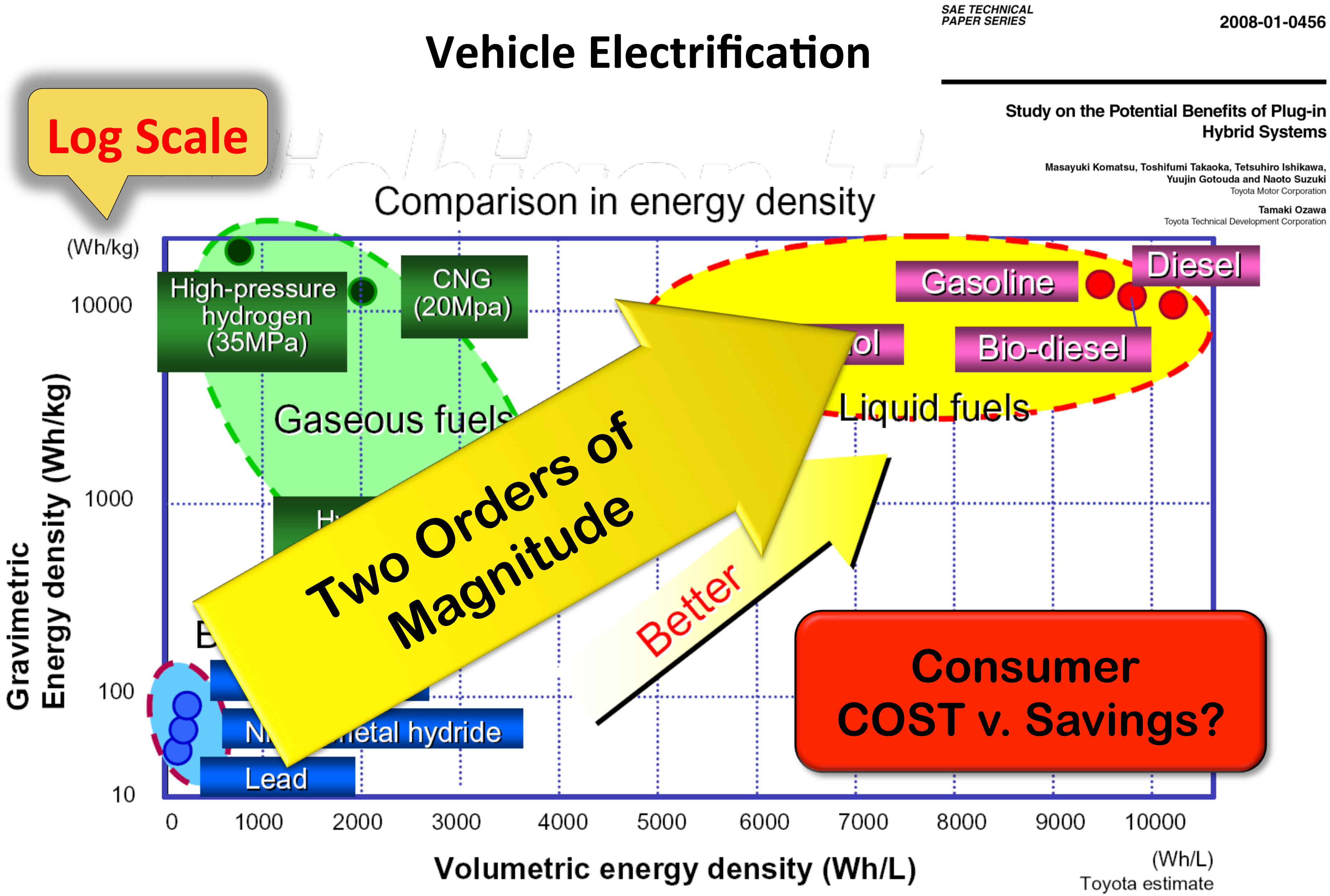
Fuel Economy and Fuel Consumption

- Need FC reduction technologies which can meet 20% near term and 45% long term
- Technologies are not simply cumulative nor compatible (e.g., 6sp ∅ HEV SP)



Relationships between fuel efficiency metric (MPG) and fuel consumption metric (L/100km) with US CAFE standards (○), European g(CO_2)/km specific emissions levels achieved (Δ) and targets (∇), and California (CA) proposed CO_2 equivalent greenhouse gas emissions standards (□). Also included are US CAFE standards scenarios which call for 3, 4 and 5% reductions in greenhouse gas emissions per year from 2016 levels
(225 g(CO2)/mile for passenger vehicles) to 2025

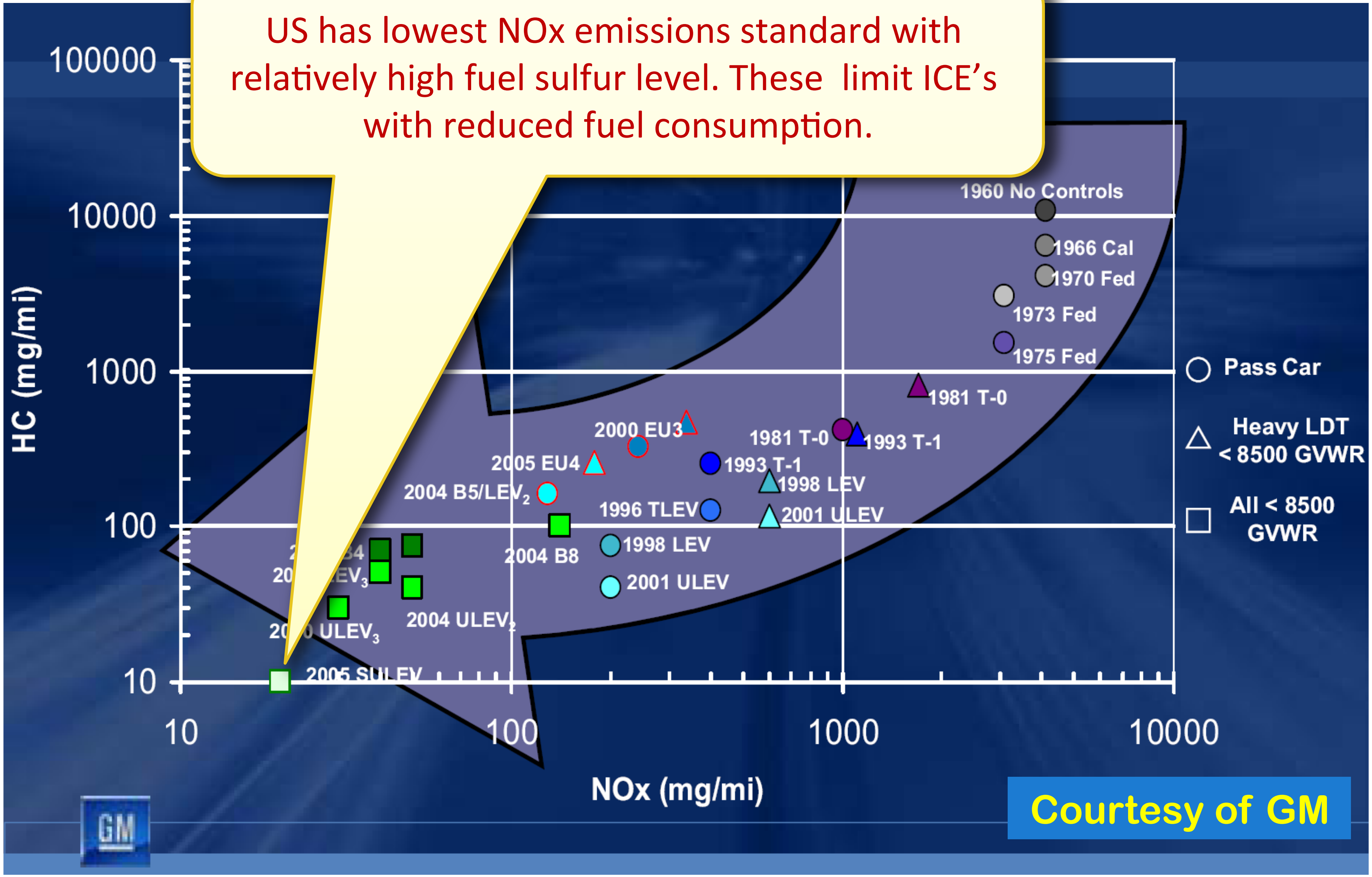
Vehicle Electrification



Battery density constraints 1-charge range of pure EV.
Combine HV and EV to reduce fuel consumption of HV.

Emissions Standards - History

US has lowest NOx emissions standard with relatively high fuel sulfur level. These limit ICE's with reduced fuel consumption.



LDV - Average Compliance Margins

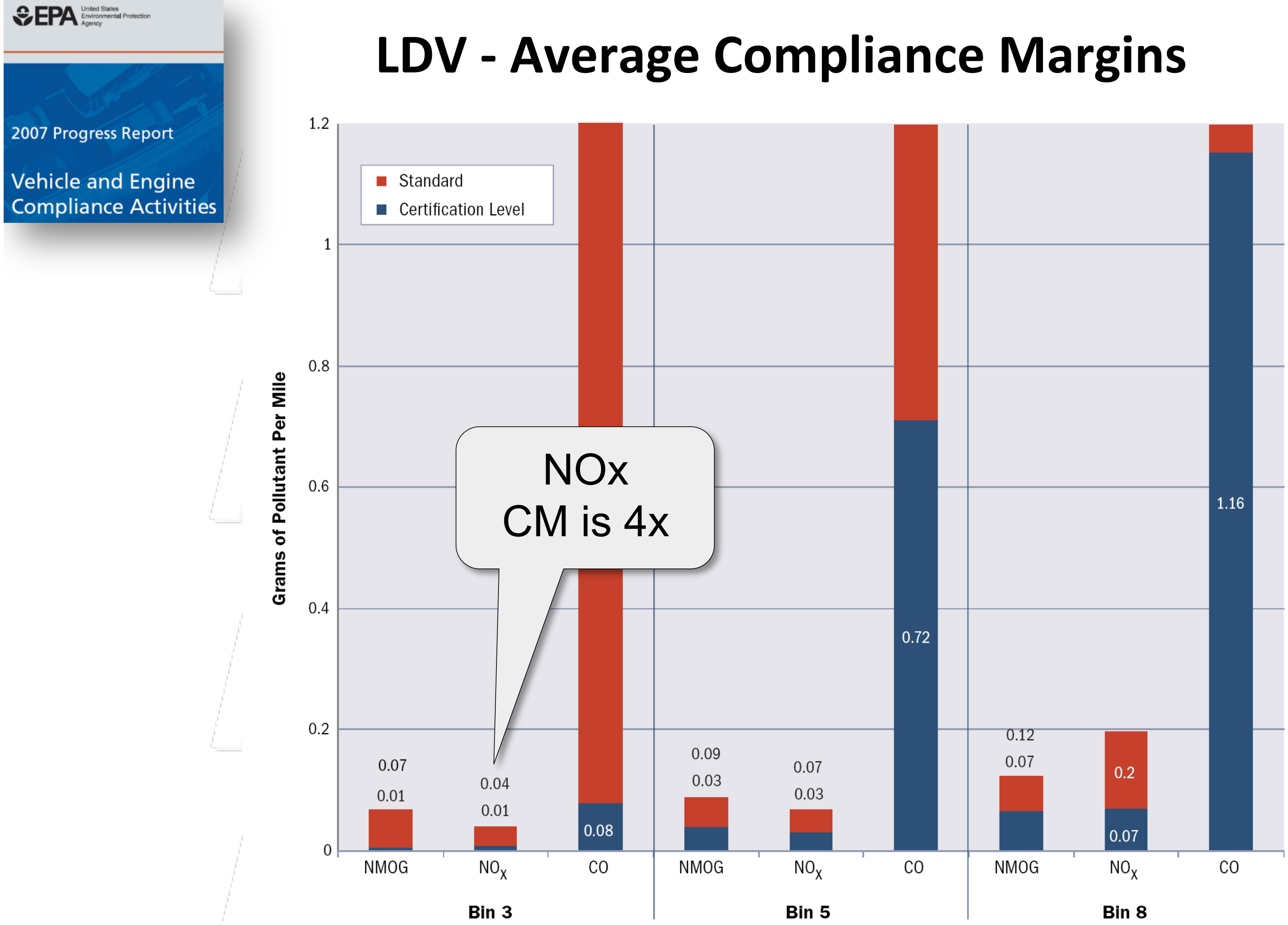


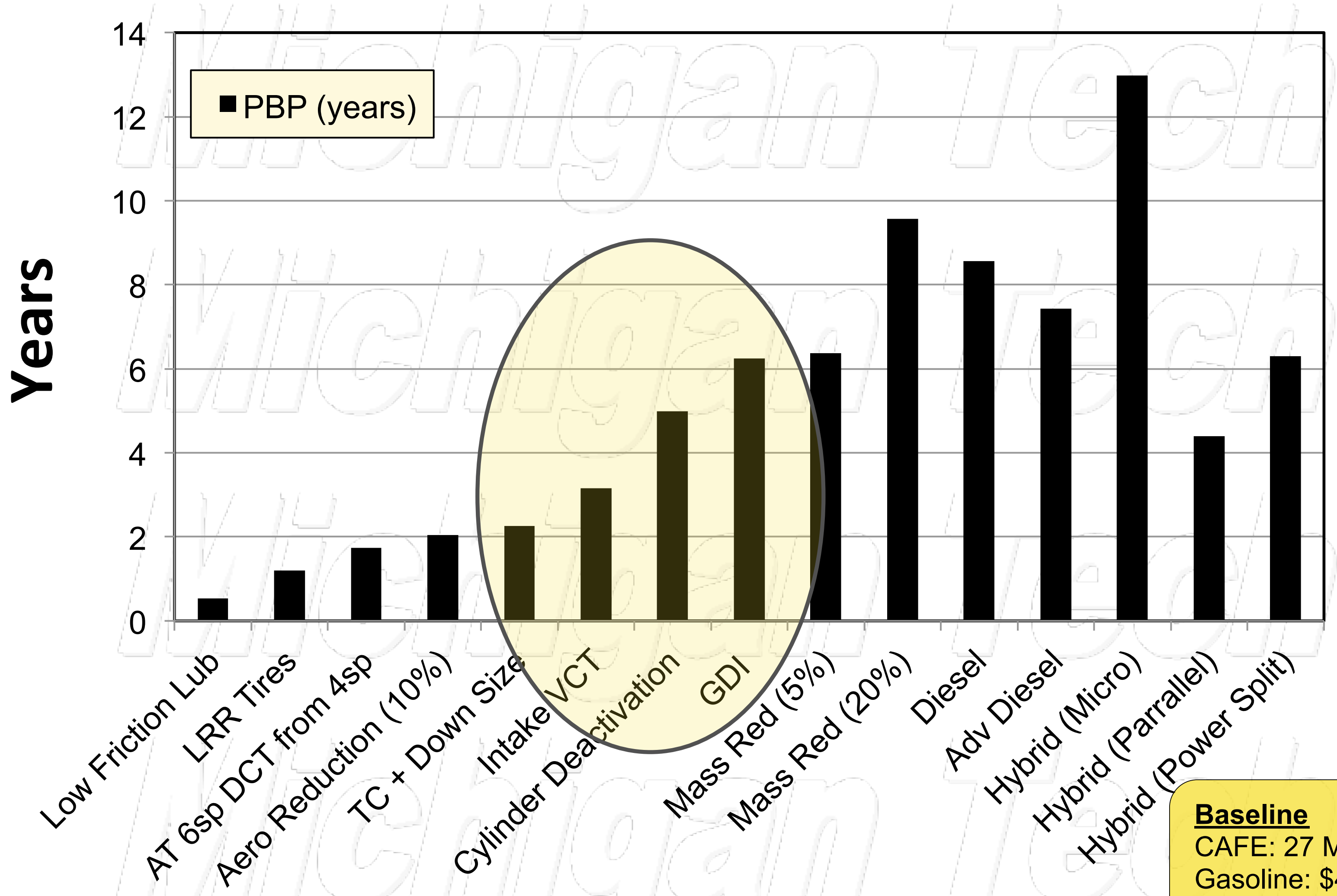
Figure 37. Tier 2 Bin Certification Levels and Compliance Margins

Exhaust Emissions

- Tier II / Bin II: 0.02 gm-NOx/mile
- Compliance Factor: 4
- Fuel Economy: 35 mile/gallon
- Exhaust NOx: **2.5 ppm** = 2.5/1,000,000

Engine Tech	Fuel Economy	NOx Engine Out	Required Aftertreatment
SI Stoich	35	500	99.5
Diesel	44*	100	98
HCCI	44*	10	80

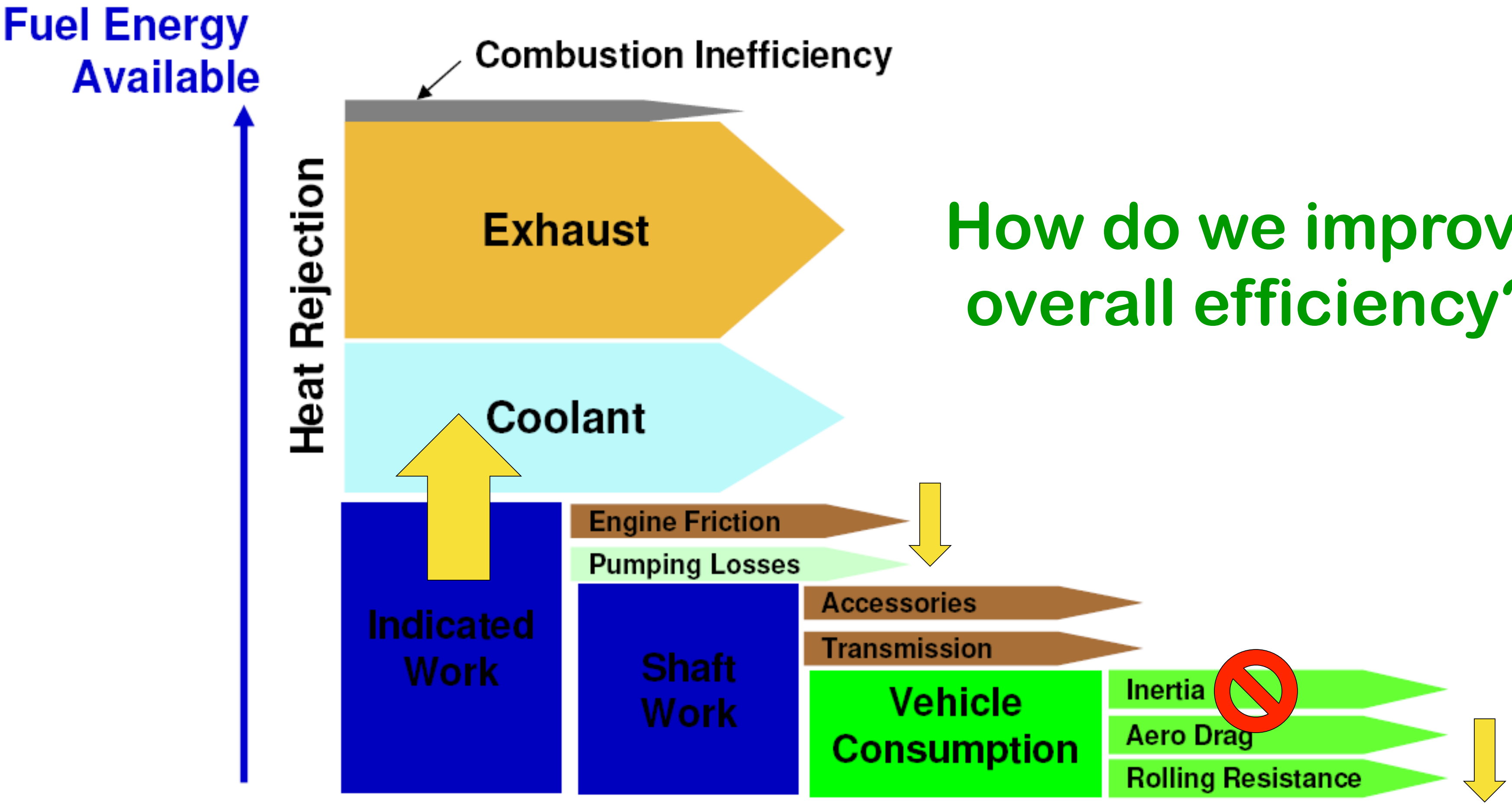
Consumer Payback Period (NAE Report Based)



Baseline
CAFE: 27 MPG
Gasoline: $4.00/gal
Driving: 15,000 miles/year

Improving Efficiency

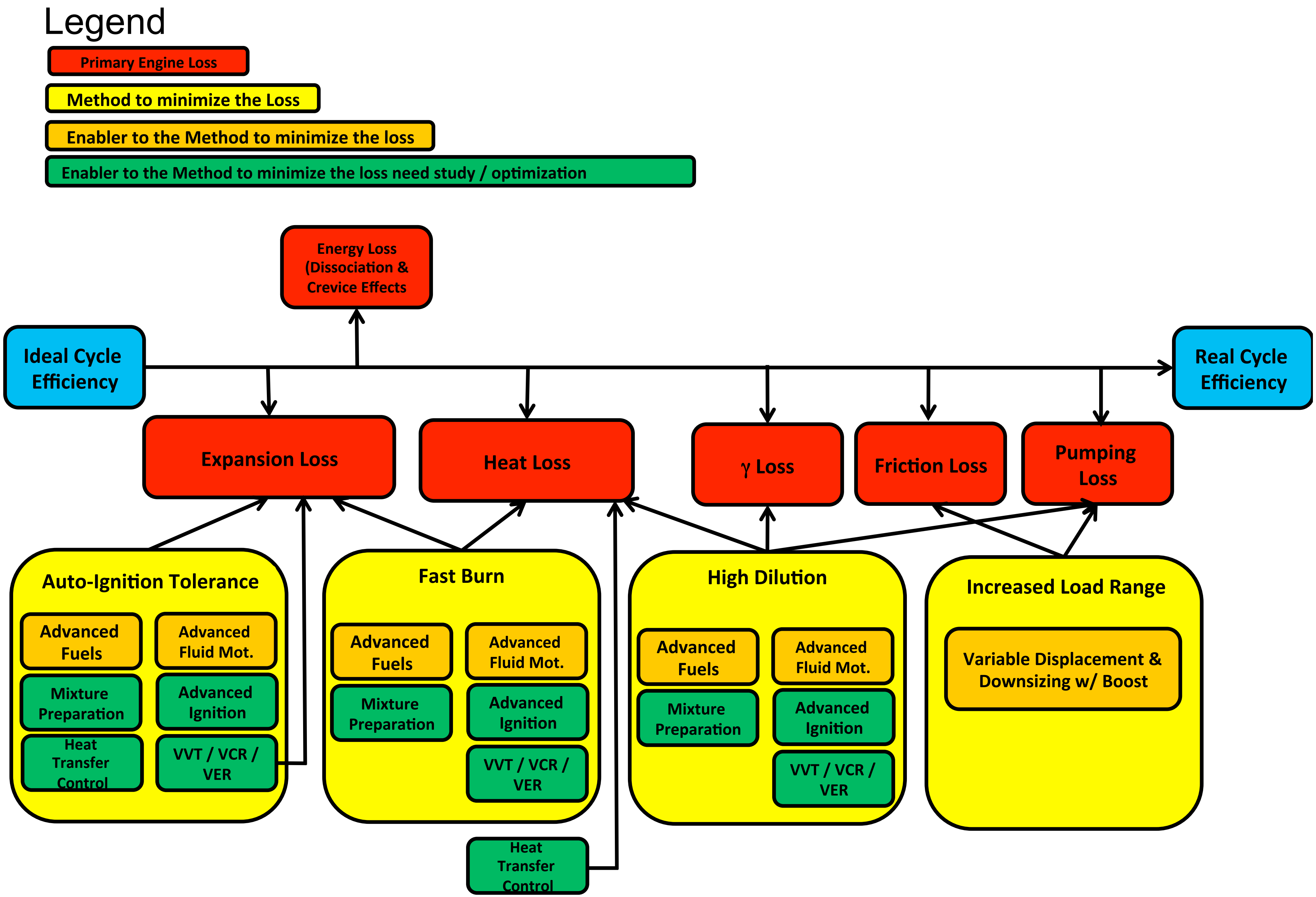
IC Engines – Baseline and Improvement



How do we improve overall efficiency?

Source: Nat'l Acad Eng. (2002)

Engine Technologies to Improve Efficiency



IC Engine Losses

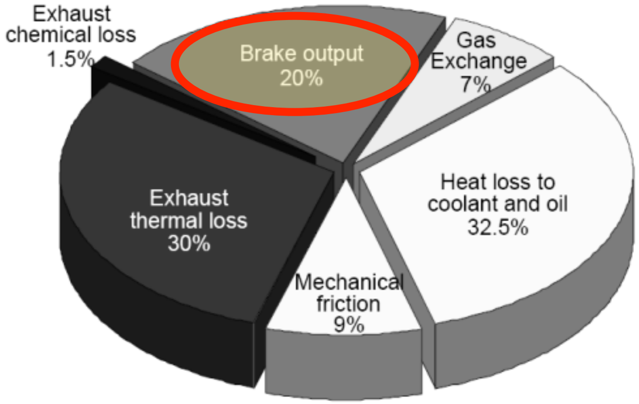


Figure 1. Typical engine losses at part load

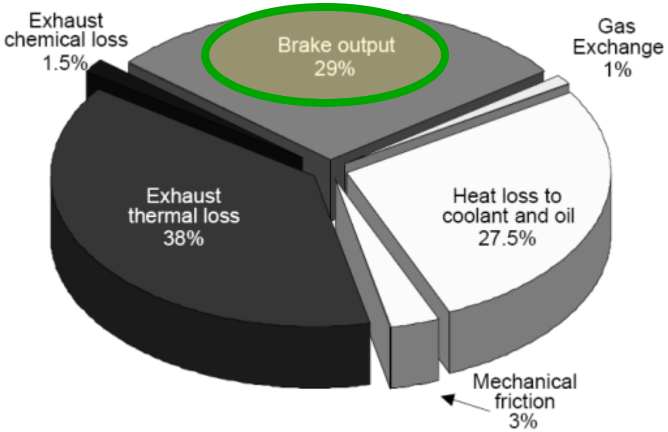
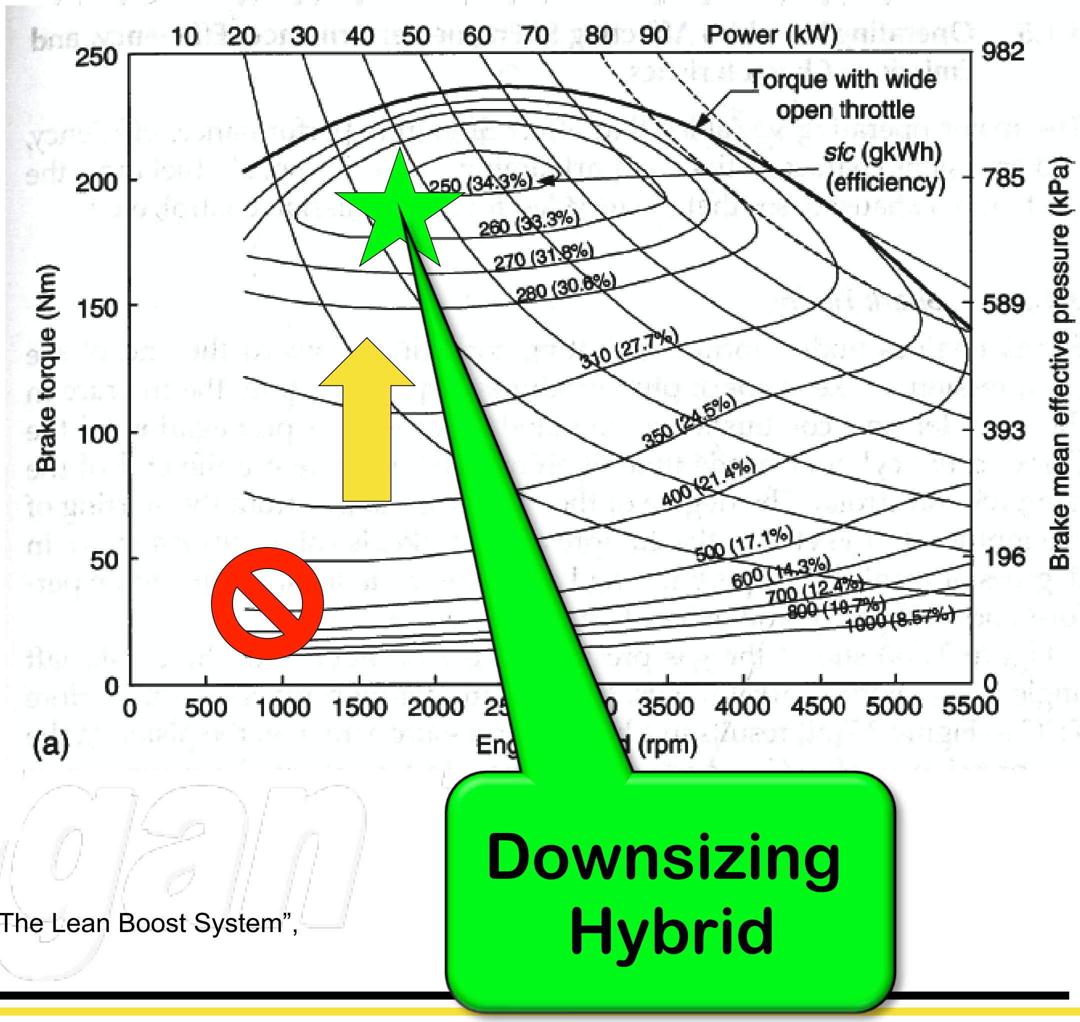


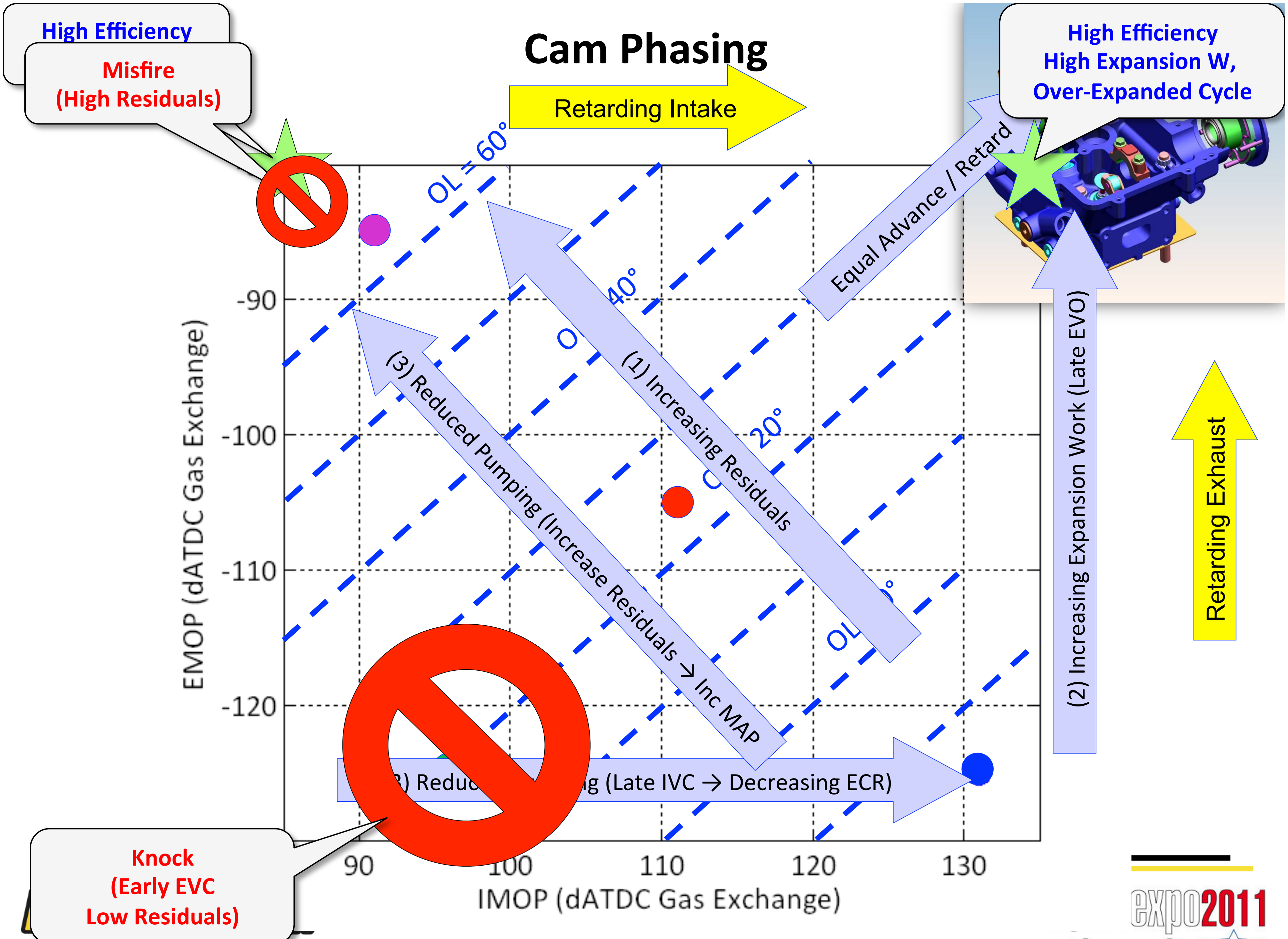
Figure 2. Typical engine losses at full load



Stokes,J., Lake,T.H., Osborne,R.J.,
"A Gasoline Engine Concept for Improved Fuel Economy – The Lean Boost System",
SAE Technical Paper 2000-01-2902.

Technologies

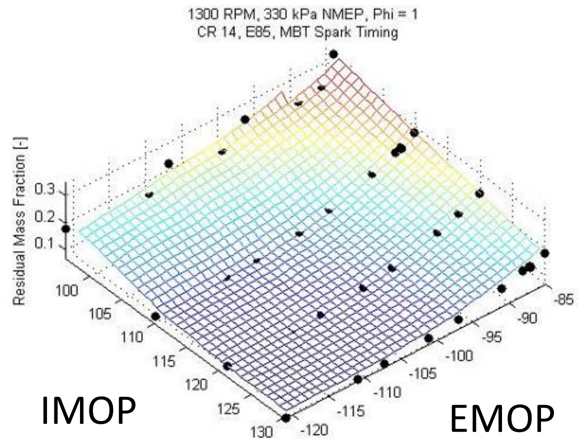
Cam Phasing



Create the Future

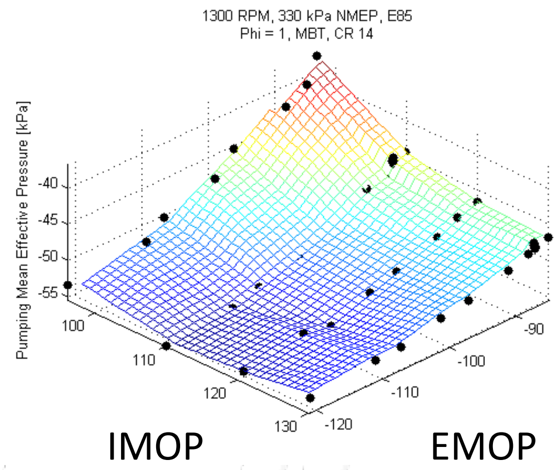
expo2011 north america

Results – DICP

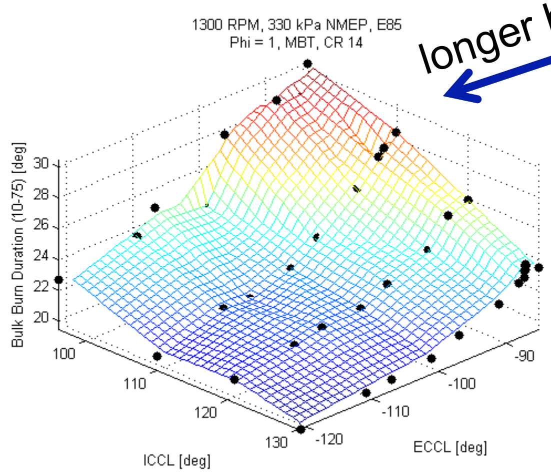


Effects of residual:

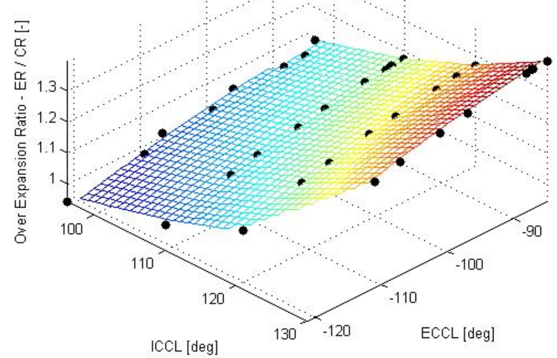
Less pumping work



longer burn durations



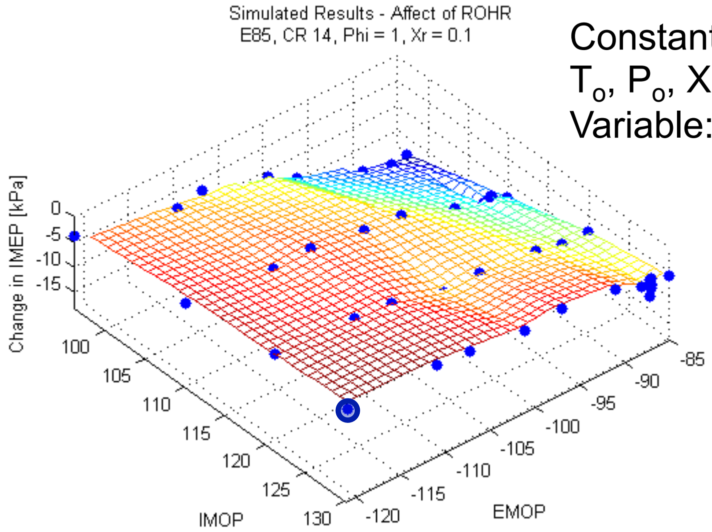
Affect of "L-IVC"



Q: How do we quantify the affects:
Burn duration
Over-expansion ratio

A: With the closed cycle simulation!

Results – DICP

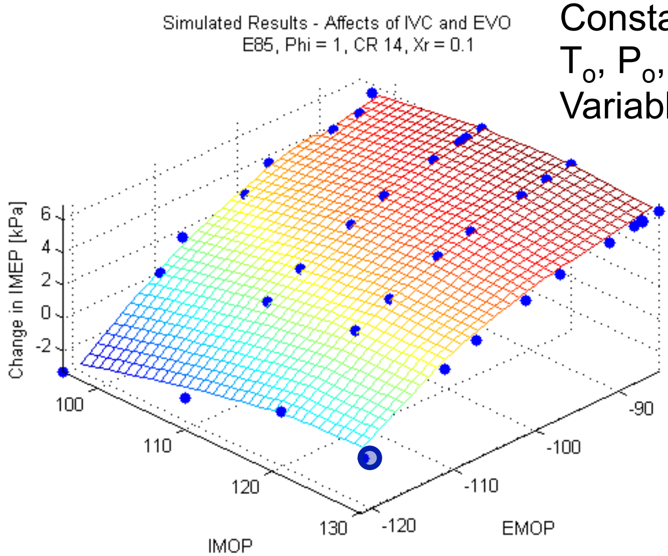


Constant:
T_o, P_o, Xr, CR, ER
Variable: **ROHR**

Simulation uses constant fuel energy:
560 J/cyc gives 375 kPa IMEP @ reference

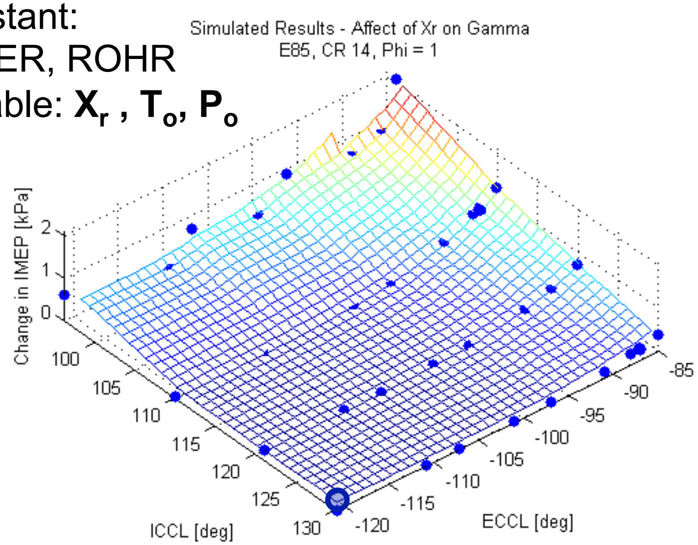
Representative of 330 kPa NMEP

Low residual – High residual	
Burn duration:	18.3 kPa MEP
Pumping:	17.9 kPa MEP
Over expansion:	5.5 kPa MEP
Gas properties:	2.1 kPa MEP



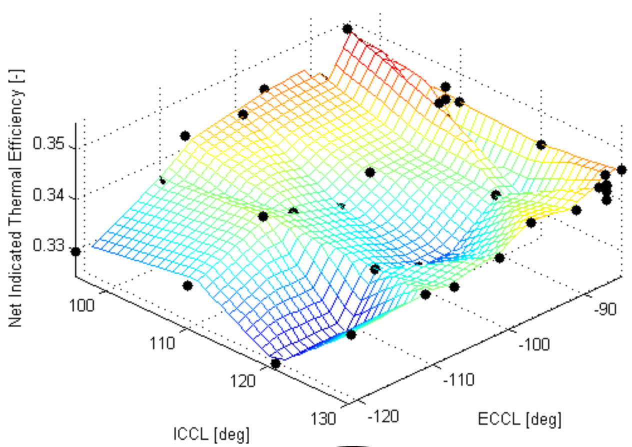
Constant:
T_o, P_o, Xr, ROHR
Variable: **CR, ER**

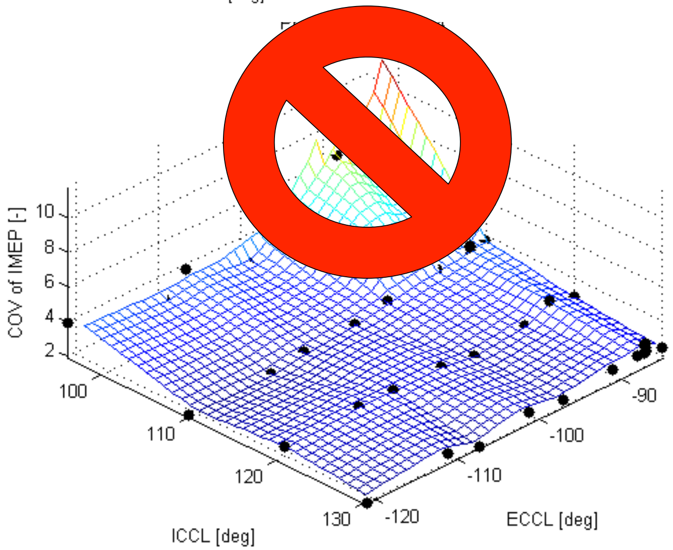
Constant:
CR, ER, ROHR
Variable: **X_r , T_o, P_o**



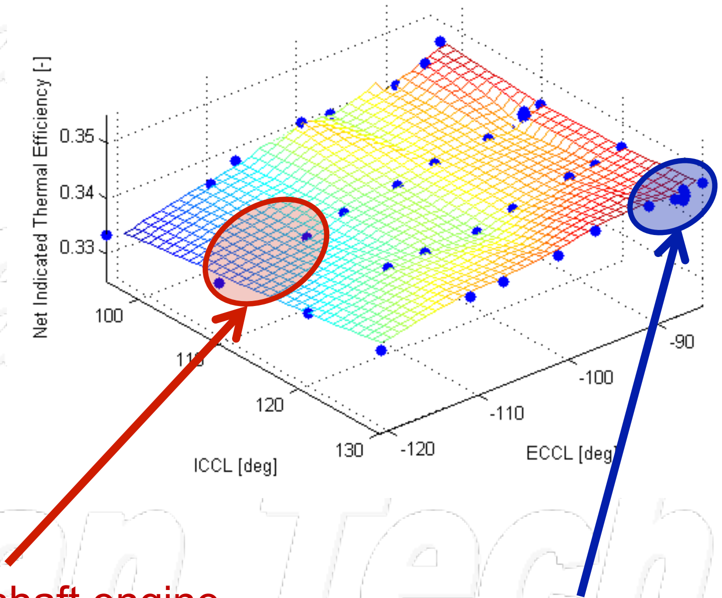
Results – DICP

Measured Results



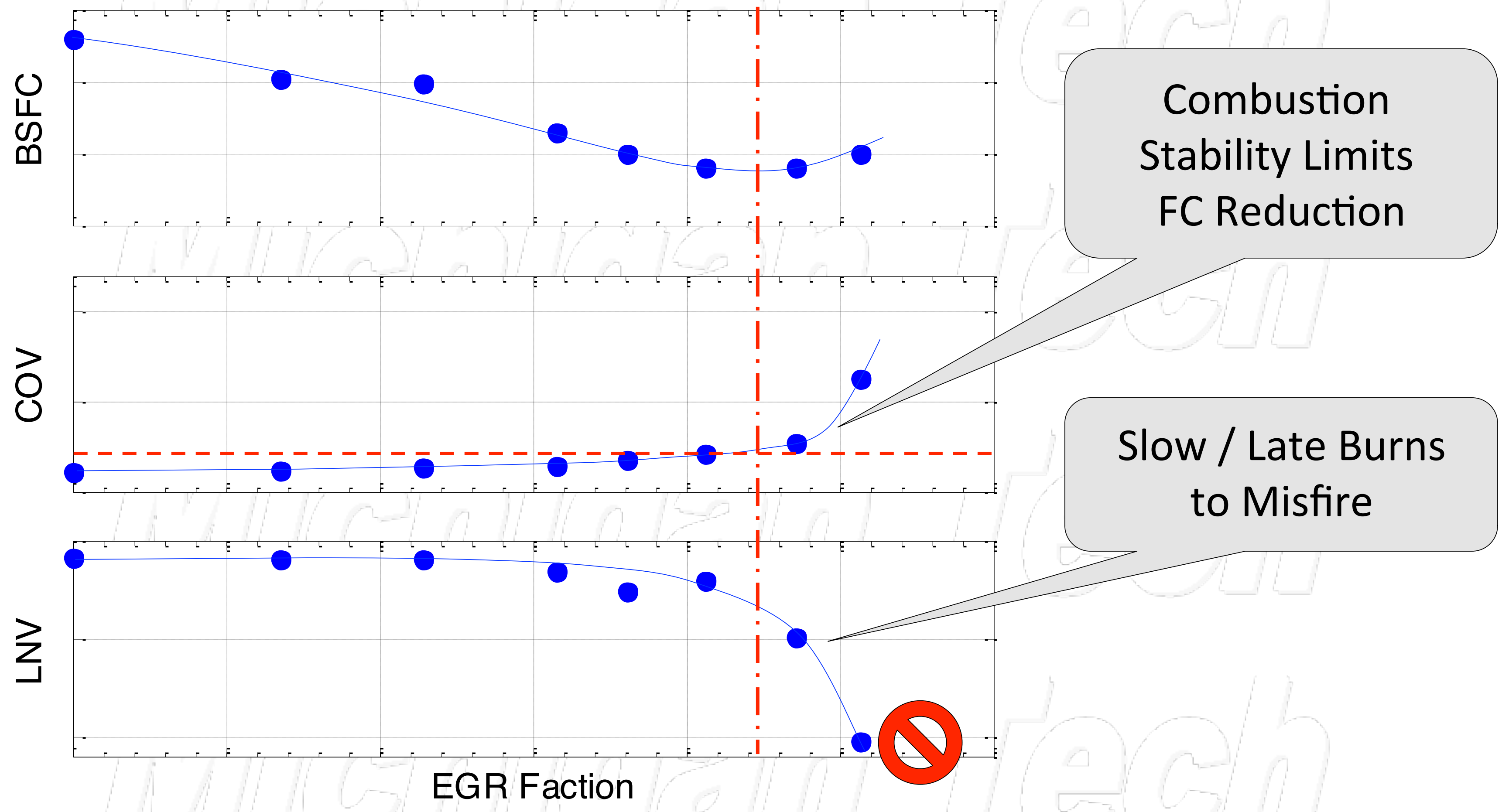


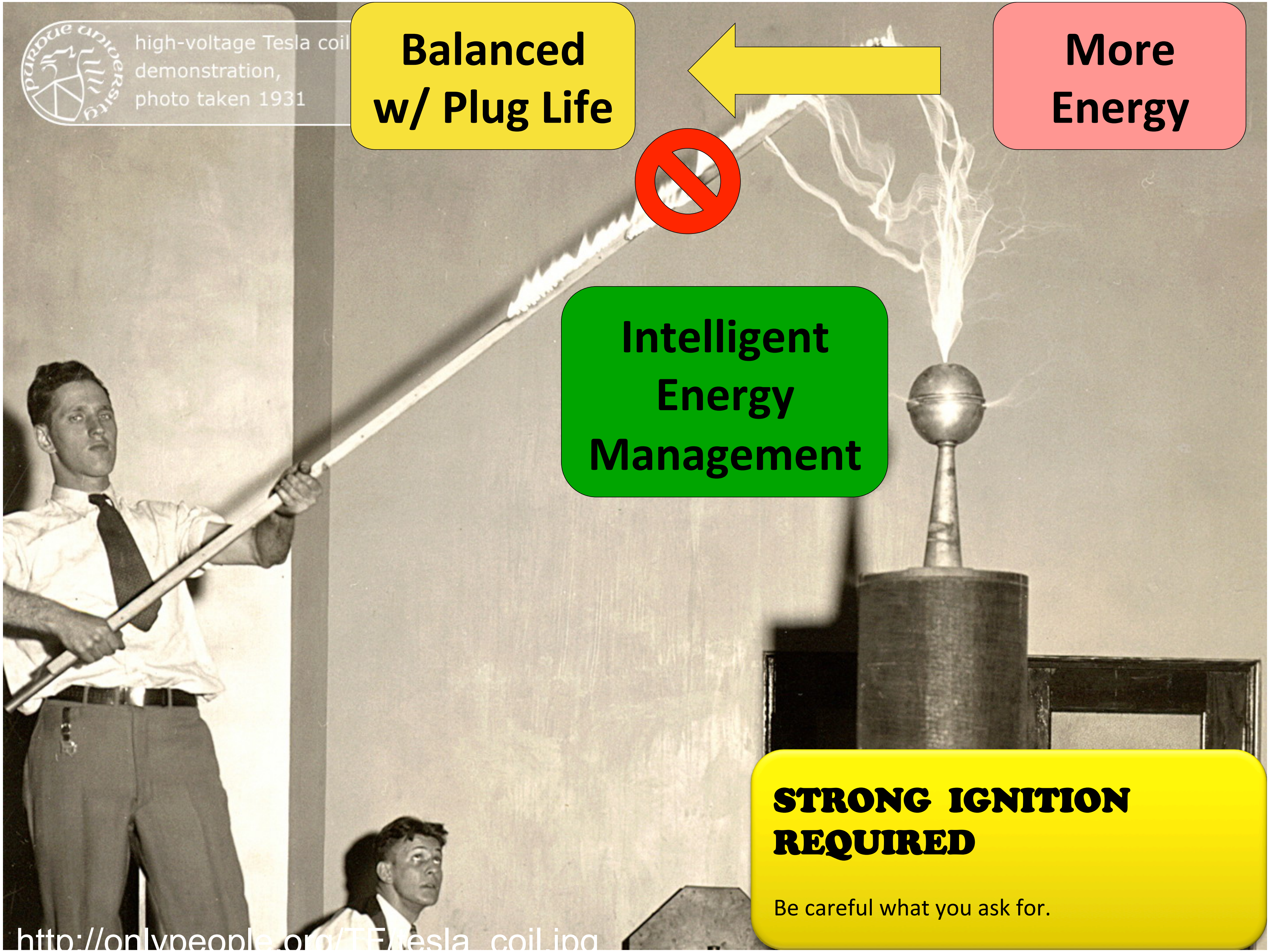
Simulation Results



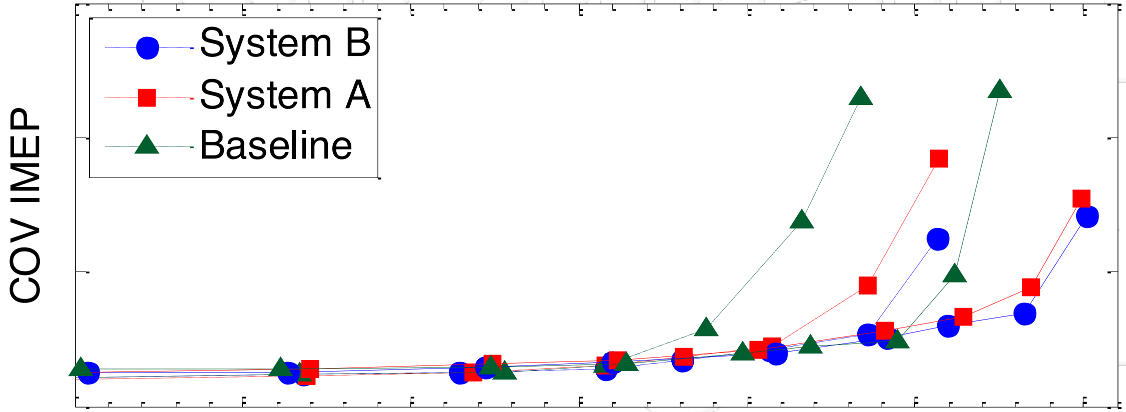
Rouse, Part Load Combustion Characterization Of Ethanol-Gasoline Fuel Blends In A Single Cylinder Spark Ignition Direct Injection Variable Cam Timing Variable Compression Ration Engine, M.S., Thesis, MTU, 2009.

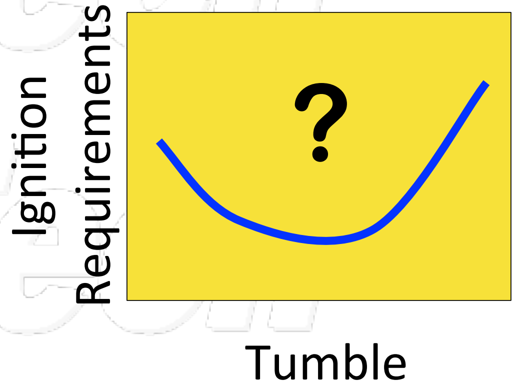
Operate Near Dilution Limit for Lowest FC

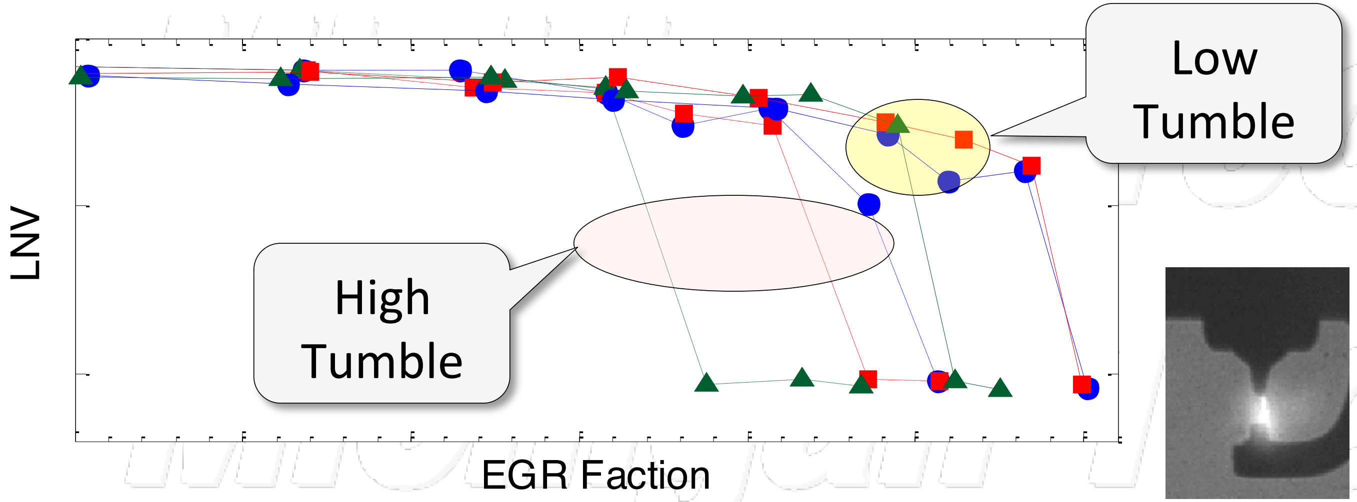


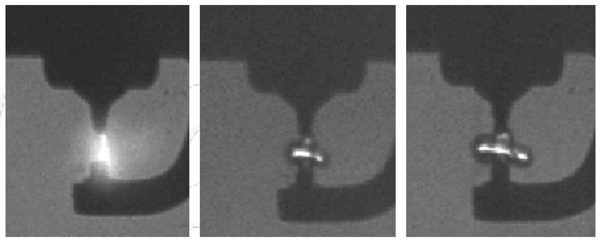

high-voltage Tesla coil demonstration, photo taken 1931
Balanced w/ Plug Life
More Energy
Intelligent Energy Management
STRONG IGNITION REQUIRED
Be careful what you ask for.
http://onlypeople.org/TF/tesla_coil.jpg

Improving Ignition System Performance Without High Energy

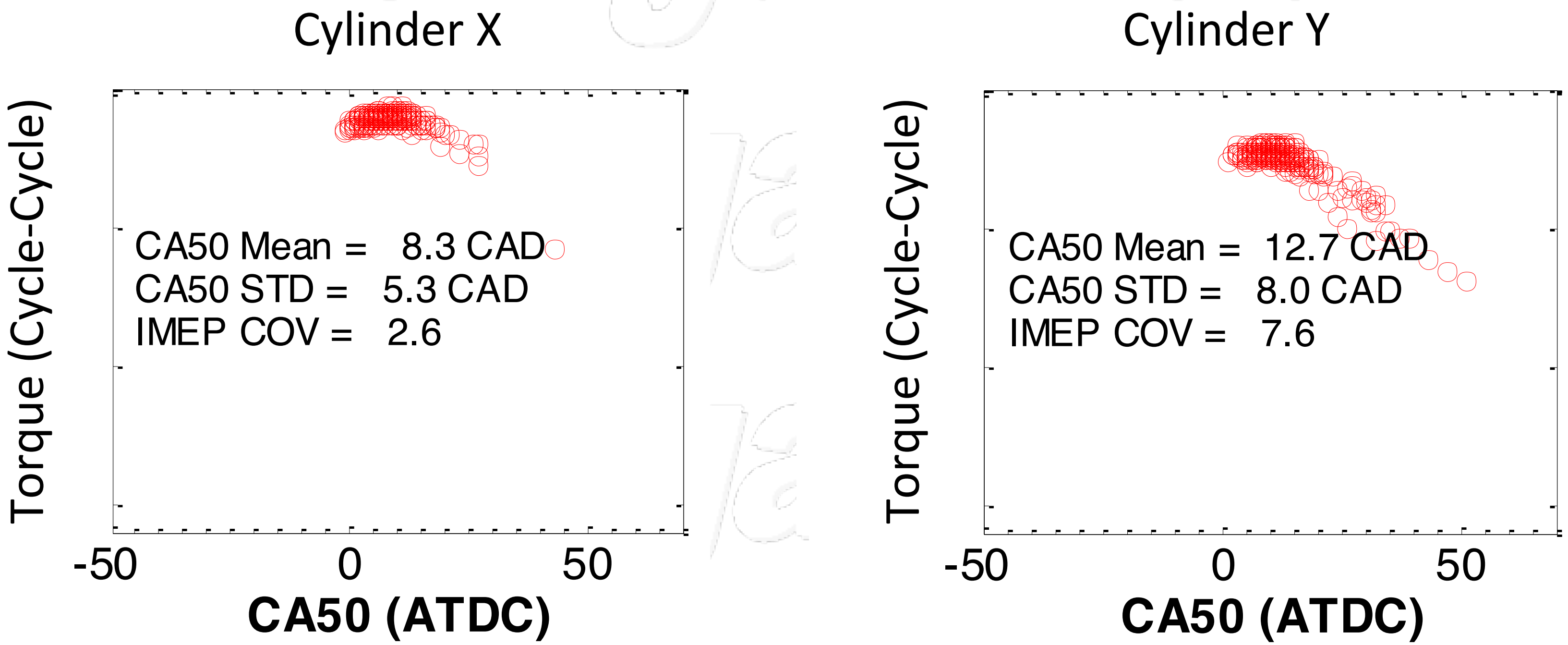








Individual Cylinder Sensing Control for Operational Robustness at Combustion Limits



Where are we headed?

- **Fuels ⇒ Expanding**
  - Gasoline/Ethanol/Butanol/NG ⇒ Hyperflex fuel
- **Gasoline Direct Injection ⇒ It's Here**
- **Advanced Charge Control ⇒ Coming On Strong**
  - Boosting
  - Valving: Optimizing dilution, charge motion, CR/ER
  - Charge Motion
  - External EGR
- **Sensing and Controls: Combustion, Emissions ⇒ NEEDED!**

Diesel ⇔ SI GDI

Thank You

Acknowledgements

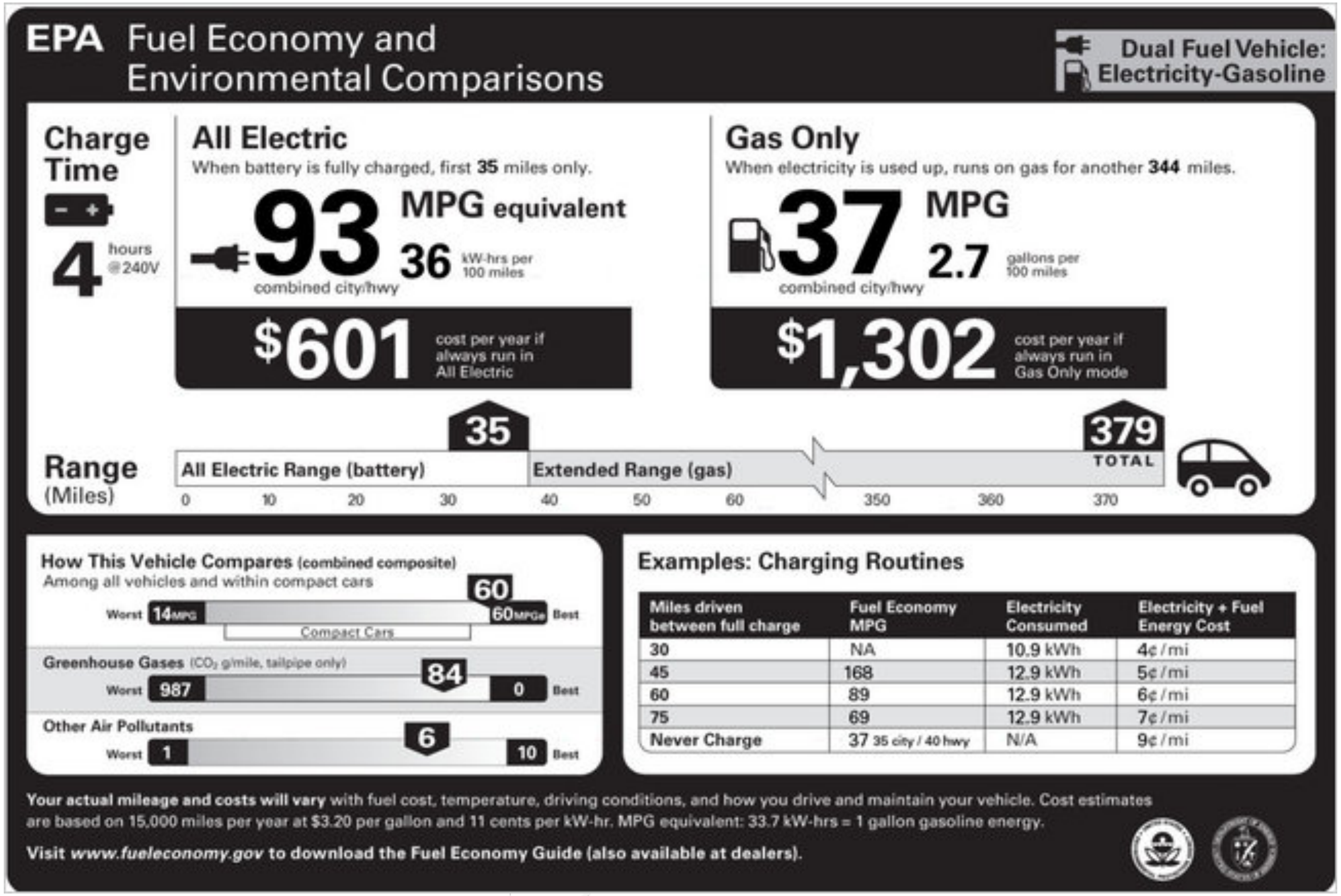
- Ford, GM, DOE, MPSC, NSF, MAGMA, ESD
- MTU Faculty, Staff and Students

Michigan Tech

Student Enrollment 7200
83% in STEM

BACKUP

Volt Fuel Economy Label



EPA Fuel Economy and Environmental Comparisons

Dual Fuel Vehicle: Electricity-Gasoline

Charge Time
4 hours @240V

All Electric
When battery is fully charged, first **35** miles only.
93 MPG equivalent
36 kW-hrs per 100 miles
combined city/hwy
$601 cost per year if always run in All Electric

Gas Only
When electricity is used up, runs on gas for another **344** miles.
37 MPG
2.7 gallons per 100 miles
combined city/hwy
$1,302 cost per year if always run in Gas Only mode

Range (Miles)
All Electric Range (battery) 35
Extended Range (gas)
379 TOTAL
0 10 20 30 40 50 60 350 360 370

How This Vehicle Compares (combined composite)
Among all vehicles and within compact cars
Worst 14MPG — 60 — 60MPGe Best
Compact Cars

Greenhouse Gases (CO_2 g/mile, tailpipe only)
Worst 987 — 84 — 0 Best

Other Air Pollutants
Worst 1 — 6 — 10 Best

Examples: Charging Routines

Miles driven between full charge	Fuel Economy MPG	Electricity Consumed	Electricity + Fuel Energy Cost
30	NA	10.9 kWh	4¢/mi
45	168	12.9 kWh	5¢/mi
60	89	12.9 kWh	6¢/mi
75	69	12.9 kWh	7¢/mi
Never Charge	37 35 city / 40 hwy	N/A	9¢/mi

Your actual mileage and costs will vary with fuel cost, temperature, driving conditions, and how you drive and maintain your vehicle. Cost estimates are based on 15,000 miles per year at $3.20 per gallon and 11 cents per kW-hr. MPG equivalent: 33.7 kW-hrs = 1 gallon gasoline energy.

Visit *www.fueleconomy.gov* to download the Fuel Economy Guide (also available at dealers).

Emissions Standards - US Tier II Light Duty Vehicle

Bin#	FTP 75 (g/mile), Full useful life (10 years‡, 120,000 miles)				
	NMOG*	CO	NOx†	PM	HCHO**
8	0.125	4.2	0.20	0.02	0.018
7	0.090	4.2	0.15	0.02	0.018
6	0.090	4.2	0.10	0.01	0.018
5	**0.090**	**4.2**	**0.07**	**0.01**	**0.018**
4	0.070	2.1	0.04	0.01	0.011
3	0.055	2.1	0.03	0.01	0.011
2	0.010	2.1	0.02	0.01	0.004
1	0	0	0	0	0

Fleet Ave

* for diesel fueled vehicle, NMOG (non-methane organic gases) means NMHC (non-meth

† average manufacturer fleet NOx standard is 0.07 g/mi for Tier 2 vehicles

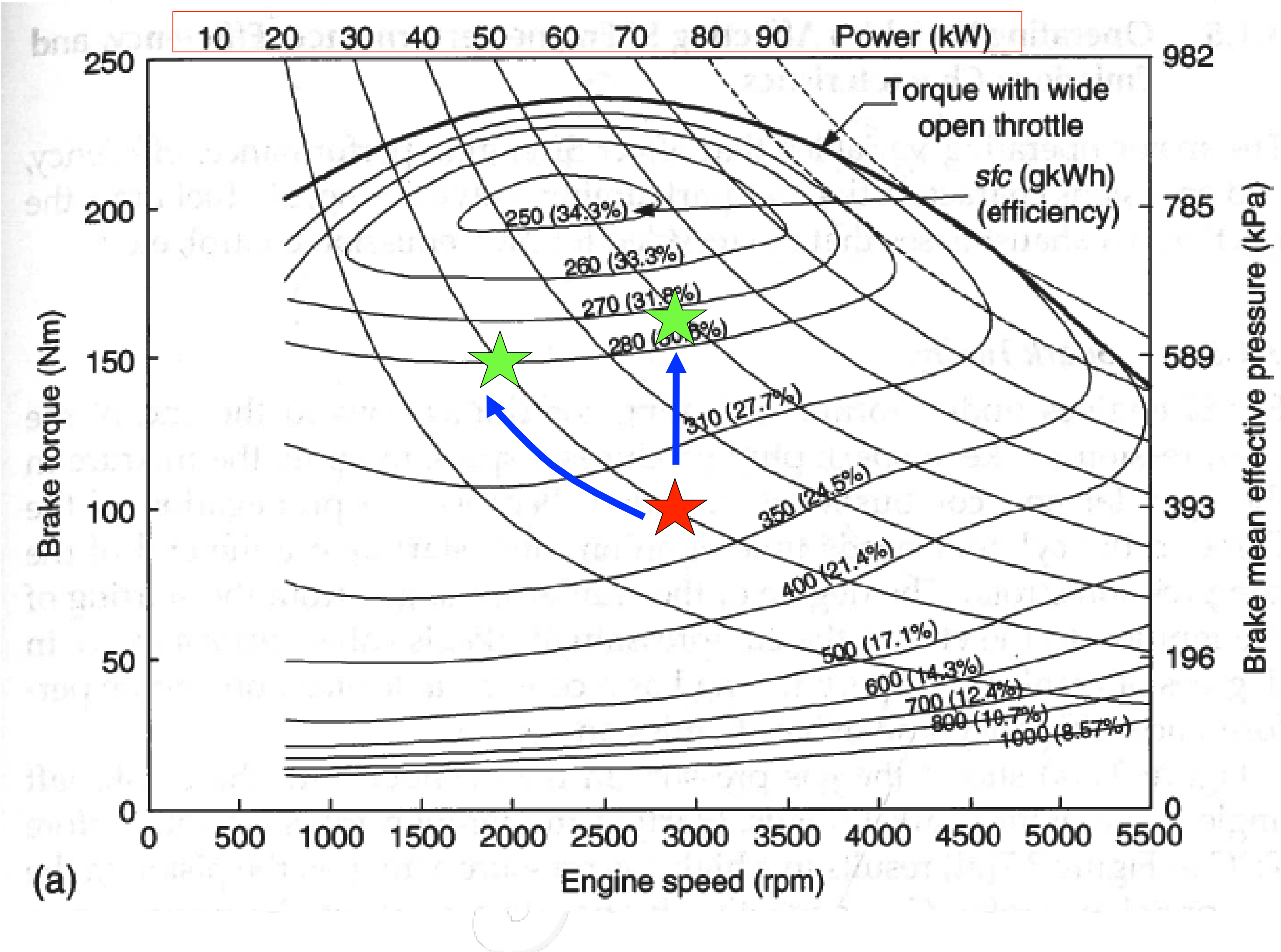
‡ 11 years for Heavy LDT and MDPV's

** HCHO - formaldehyde

Equivalent to CARB's Super-Ultra-Low Emissions Vehicle (SULEV)

Diesel's usually fall in Bin 8 to 5.
Require an additional 3.5x reduction to make Bin 2

BSFC Table – Constant Power Curves

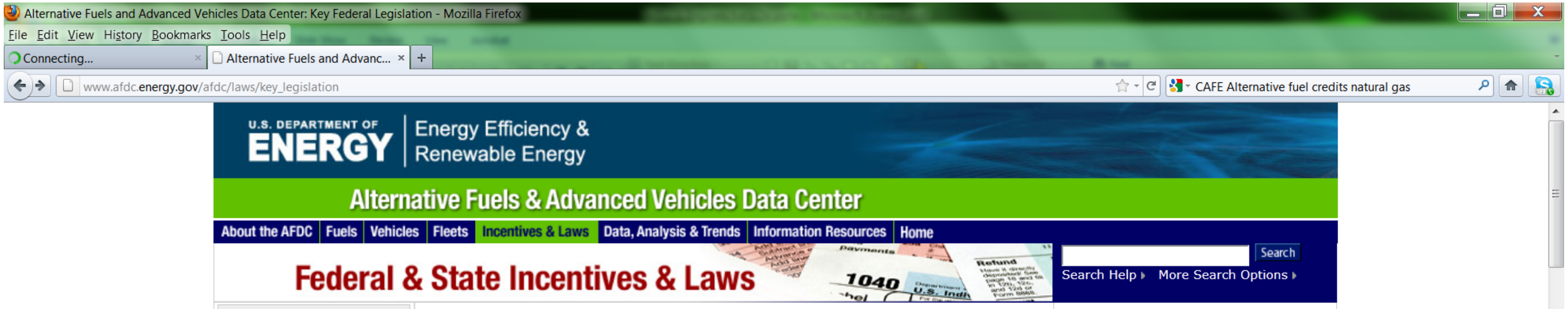


Fuels - Specific CO2 Production

	Density	MW	QLHV	g|CO2/g|fuel	S|CO2
Fuel	(kg/m3)	(kg/kgmol)	(MJ/kg)	(-)	(g-CO2/kW-hr)
Gasoline (CH1.87)	750	13.89	44.0	3.17	810
Isooctane	692	114.23	44.3	3.08	783
Methanol	792	32.04	20.0	1.37	773
Ethanol	785	46.07	26.9	1.91	799
E85	755	56.29	29.5	2.10	801
Hydrogen	0.09	2.01	120.0	0.00	0
Methane	0.72	16.04	50.0	2.74	617

HC fuels have similar CO2 production characteristics
FC/FE Regulations are equivalent to CO2 Regulations

CAFE and Alternative Fuels Credit



EPAct 1992 also defines "alternative fuels" as: methanol, **ethanol,** and other alcohols; blends of 85% or more of alcohol with gasoline (E85); natural gas and liquid fuels domestically produced from natural gas; propane; hydrogen; electricity; biodiesel (B100); coal-derived liquid fuels; fuels, other than alcohol, derived from biological materials; and P-Series fuels, which were added to the definition in 1999.

Computing NOx Emissions

Formatted Equations

Compute Exhaust Flow

$$Exh_{Mile} = FC \cdot \frac{1}{264} \cdot \frac{750}{1} \cdot (1 + AFR) \cdot 1000 \quad gm_{exh}/mile$$

Compute Mass Concentration of NOx

$$MF_{NOx} = \frac{NOx}{Exh_{Mile}}$$

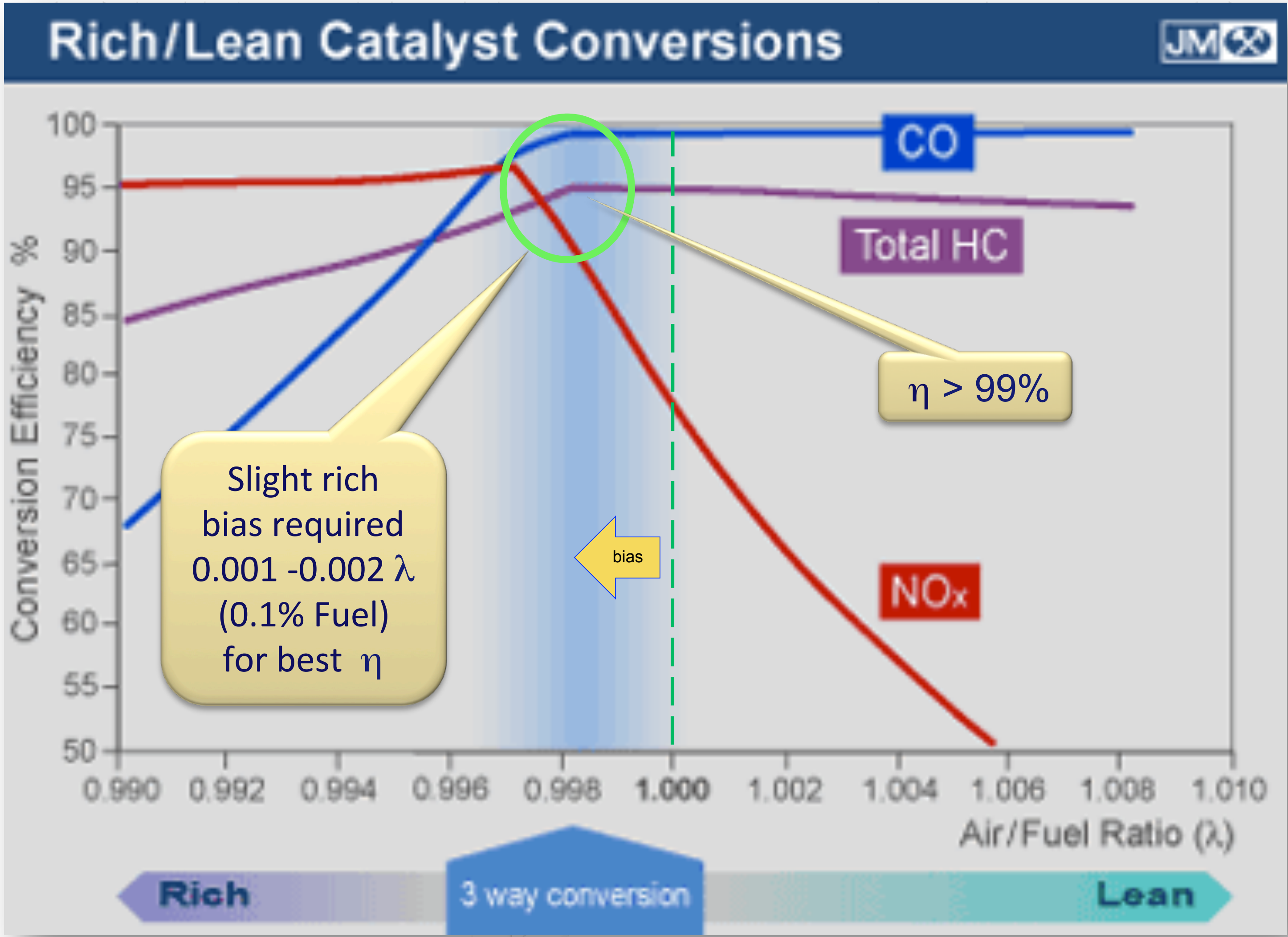
- Mole Fraction

$$Y_{NOx} = \frac{\frac{1}{MW_{NOx}}}{\frac{1}{MW_{Exh}}} \cdot MF_{NOx}$$

- Concentration in ppm

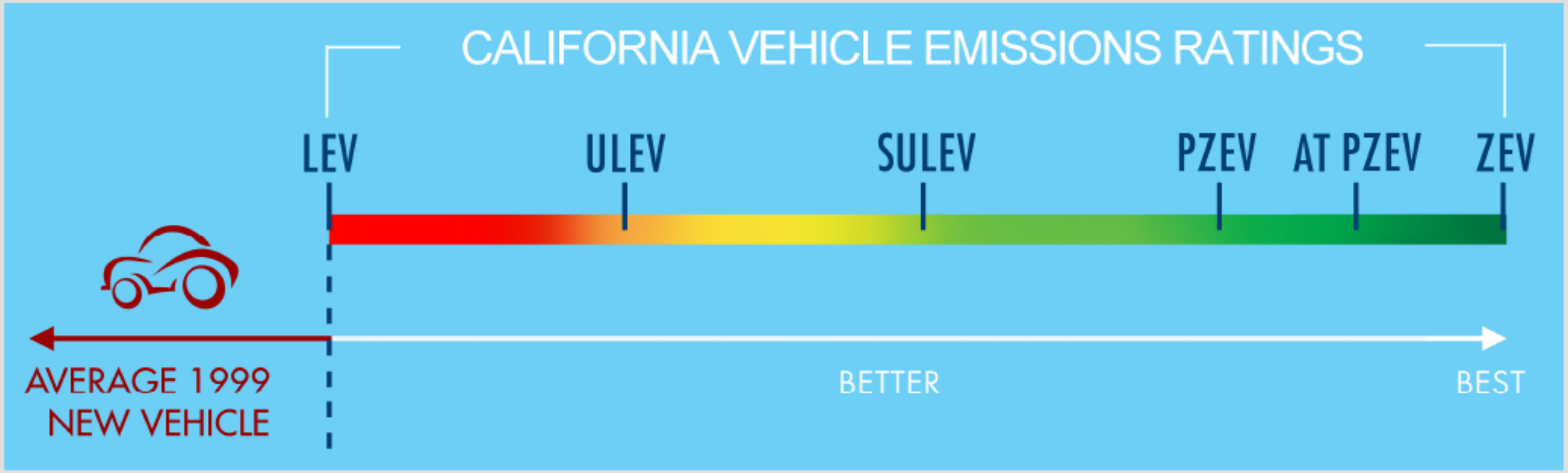
$$PPM_{NOx} = 1000000 \cdot Y_{NOx}$$

TWC - Conversion Efficiency



California Vehicle Emissions Ratings

All new vehicles sold in California must be certified with one of California's six emissions ratings. A vehicle's emissions rating is posted on the *Vehicle Emission Control Information label* under the engine hood.



LEV *(Low Emission Vehicle):*	The least stringent emission standard for all new cars sold in California.
ULEV *(Ultra Low Emission Vehicle):*	50% cleaner than the average new model year vehicle.
SULEV *(Super Ultra Low Emission Vehicle):*	90% cleaner than the average new model year vehicle.
PZEV *(Partial Zero Emission Vehicle):*	Meets SULEV tailpipe emission standards, has a 15-year / 150,000 mile warranty and has zero evaporative emissions[1].
AT PZEV *(Advanced Technology PZEV):*	Meets SULEV tailpipe emission standards, has a 15-year / 150,000 mile warranty, has zero evaporative emissions and includes advanced technology components.
ZEV *(Zero Emission Vehicle):*	Zero tailpipe emissions, and 98% cleaner than the average new model year vehicle.

[1] *Evaporative emissions are stored fuel vapors that escape to the outside*

"Driveclean.ca.gov fact sheet: Definition of a partial zero-emissions vehicle" (PDF). California Air Resources Board. http://www.arb.ca.gov/msprog/zevprog/factsheets/driveclean.pdf.

California - ZEV Program

Which types of vehicles are included in the Zero Emission Vehicle (ZEV) Program?

Category	Vehicle Acronym	Technology
"Gold"	ZEV	Battery, hydrogen fuel cell
"Silver Plus"*	Enhanced AT PZEV	AT PZEV using a ZEV fuel such as electricity or hydrogen. Examples include plug-in hybrids or hydrogen internal combustion engine vehicles.
"Silver"	AT PZEV	Hybrid, compressed natural gas, methanol fuel cell
"Bronze"	PZEV	Extremely clean conventional vehicle with extended warranty and reduced evaporative emissions

SI Engine Powertrains with three-way catalysts (SLUEV) + reduced evaporative Emissions.

AT-PZEV - Limits diesel use for HEV's

Fact Sheet — California Environmental Protection Agency Air Resources Board

The Zero Emission Vehicle Program - 2008

Michigan Tech Create the Future

engine expo 2011 north america

California ZEV Program: 2006

Vehicle Type		Quantity
ZEV	Fuel cell	160
	Battery electric	4,400
	Neighborhood electric	26,000
AT PZEV	Hybrid, or Compressed Natural Gas	109,000
PZEV	Conventional	672,000

Fact Sheet — California Environmental Protection Agency Air Resources Board

The Zero Emission Vehicle Program - 2008

California ZEV Program: 2012-2014

ZEV Type	Definition	Example
Type I	Electric Vehicle with 50-75 mile range	Limited Range Battery EV
Type I.5	Electric Vehicle with 75-100 mile range	City Electric Vehicle
Type II	Electric with 100-200 mile range	Full function Battery EV
Type III	100+ mile electric vehicle with fast refueling or 200 mile battery EV	Fuel Cell or Battery EV
Type IV	200+ mile electric vehicle with fast refueling	Fuel Cell
Type V	300+ mile electric vehicle with fast refueling	Fuel Cell

Phase III: 2012-2014 Timeframe			
	Options	**Vehicle Type**	**Number of Vehicles**
Gold Requirement	1	Type IV ZEV	25,000*
	OR		
	2	Type IV ZEV	7,500*
		Enhanced AT PZEVs	58,333*

*Numbers based on estimated annual sales of 1.4 million passenger cars. Actual number of ZEVs may vary with actual annual sales

California - PZEV and AT-PZEV

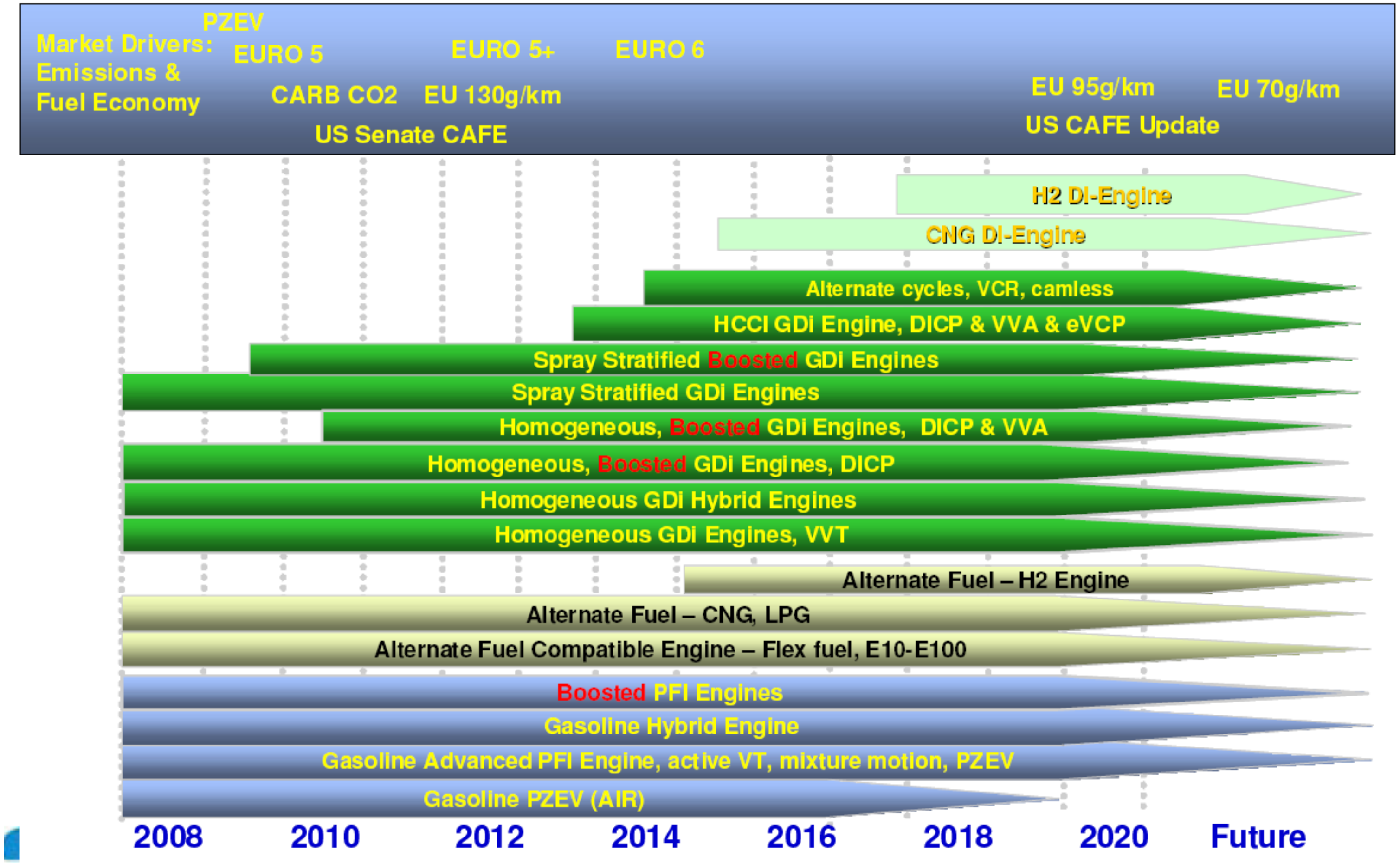
Partial Zero-Emissions Vehicle (PZEV)

PZEV = SULEV(TierII Bin2) + Zero Evaporative Emissions
+ 15-year/150,000mile Emissions Warranty

Advanced-Technology PZEV AT-PZEV

PZEV + Advanced technology to reduced GHG emissions
(hybrid / flex fuel)

High Level Gasoline Engine Technology Roadmap



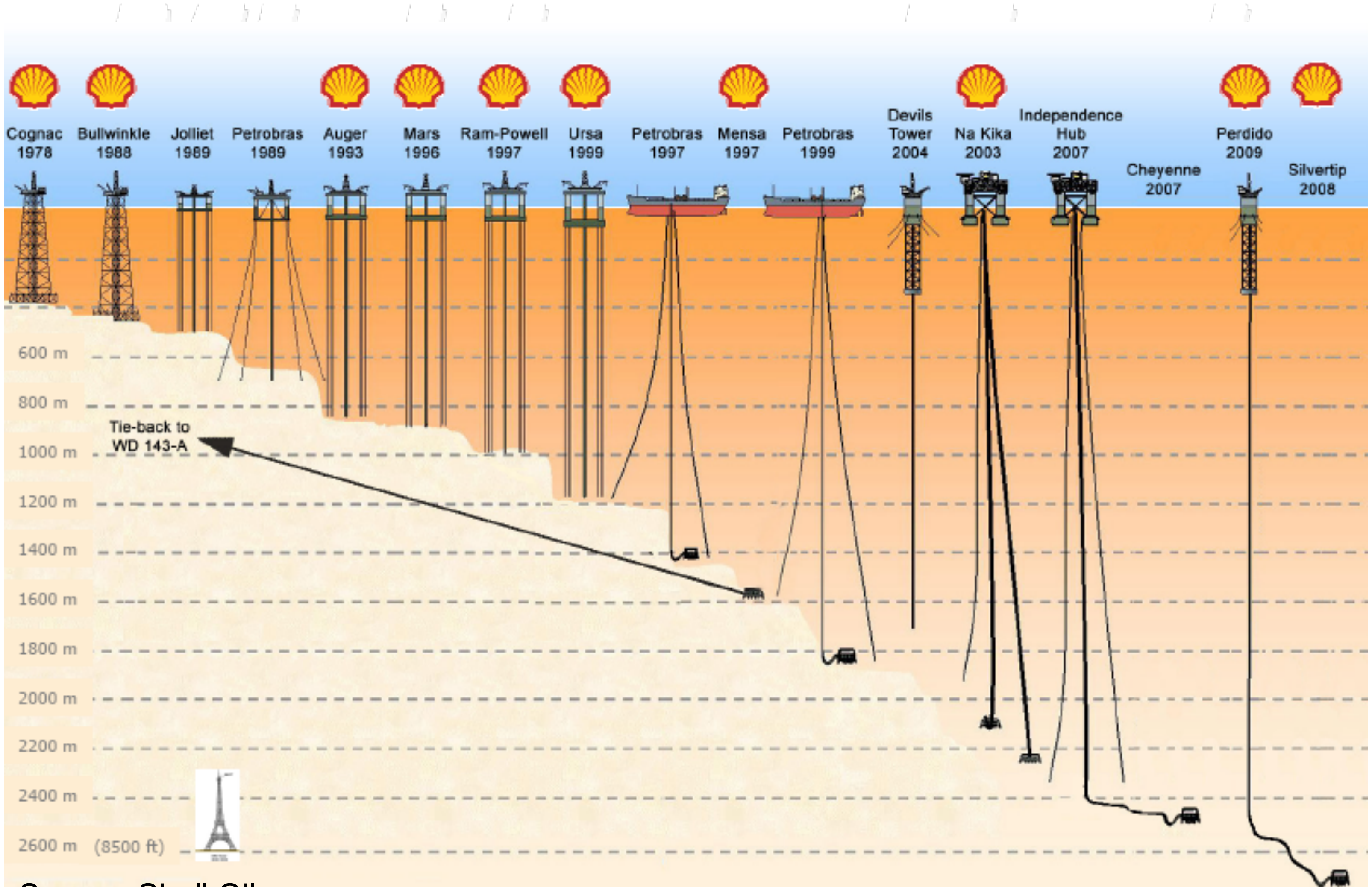
CO_2 Reduction for Spark-Ignition Engines: Two Paths to Success

Leveraging Air Delivery and Fuel Injection Technologies to Improve Engine Efficiency

John E. Kirwan
Delphi Powertrain Systems

EXTRA

Development of Oil Production



Source: Shell Oil

Energy Return

Energy Return on Energy Invested (EROEI)= Energy Out/Energy In

- Historical Conventional Oil (typical value) = 100:1 to 150:1
  (Saudi Arabia super giant Ghawar oil field, 1948 - present)
- Modern Conventional Oil (typical value) = 25:1
  (Reflecting more "difficult" oil: deepwater, tight gas, horizontal wells, 3D & 4D seismic)
- Marginal Barrel = 6:1
  (Alberta tar sands surface mining)
- New Horizon = 3:1
  (Alberta tar sand in situ [steam injection], oil shale ICP ?)
- US Corn ethanol = ~1.3 to 0.75:1

Increasing Cost and Environmental Impact