Engine Maturity, Efficiency, and Potential Improvements

John W. Fairbanks
Office of FreedomCAR and Vehicle Technologies
US Department of Energy, Washington, D.C.

Diesel Engine Emission Reduction Conference
Coronado, California
August 30, 2004

Outline

- Transportation engine development chronology
- Diesel engine development
- Transportation applications
- Current fuel situation
- Diesel potential

Diesel Engines

Are they old and mature (i.e. fully-developed technology)?

Transportation Entering The 19th Century

- Stage coach
  - 8 Passengers
  - 4 Horsepower (quadrupeds)
  - One Shilling (25¢) for 4 miles
- Bio-mass derived fuel
  - Minimally processed
- Emissions
  - Bovine methane
  - Agglomeration of macro particles
    - Minimally airborne
    - Recyclable
- Infrastructure already in place

Cecil's Hydrogen Gas Engine Concept (1820)

XIV. *On the Application of Hydrogen Gas to produce a moving Power in Machinery; with a Description of an Engine which is moved by the Pressure of the Atmosphere upon a Vacuum caused by Explosions of Hydrogen Gas and Atmospheric Air.*

BY THE REV. W. CECIL, M. A.

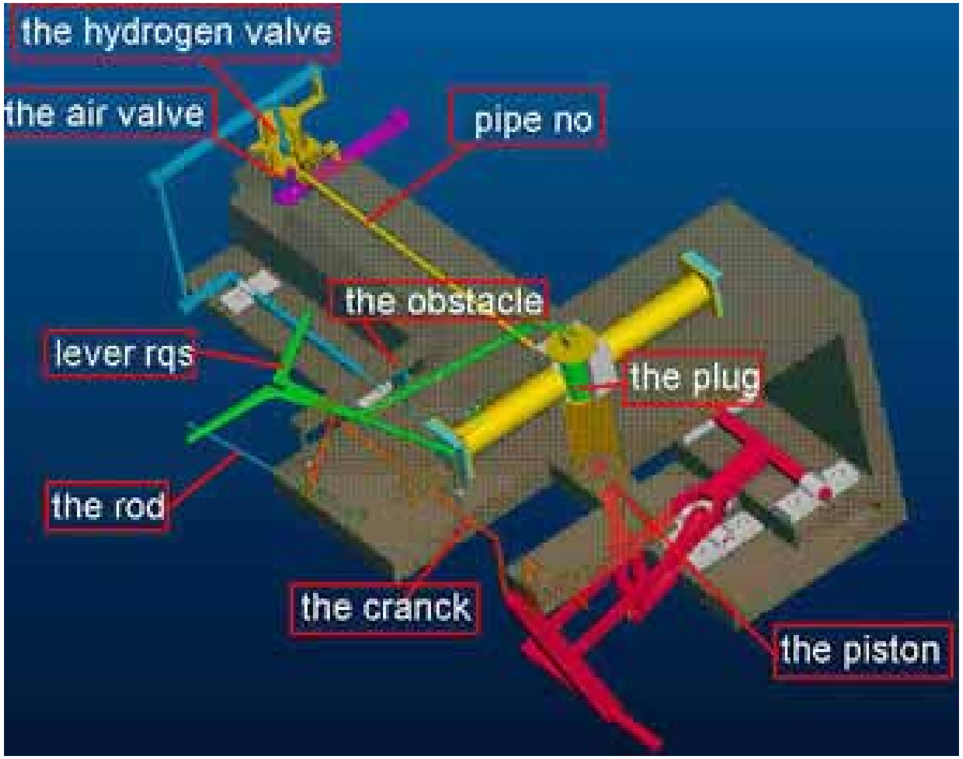
FELLOW OF MAGDALEN COLLEGE,

AND OF THE CAMBRIDGE PHILOSOPHICAL SOCIETY.

[Read *Nov.* 27, 1820.]

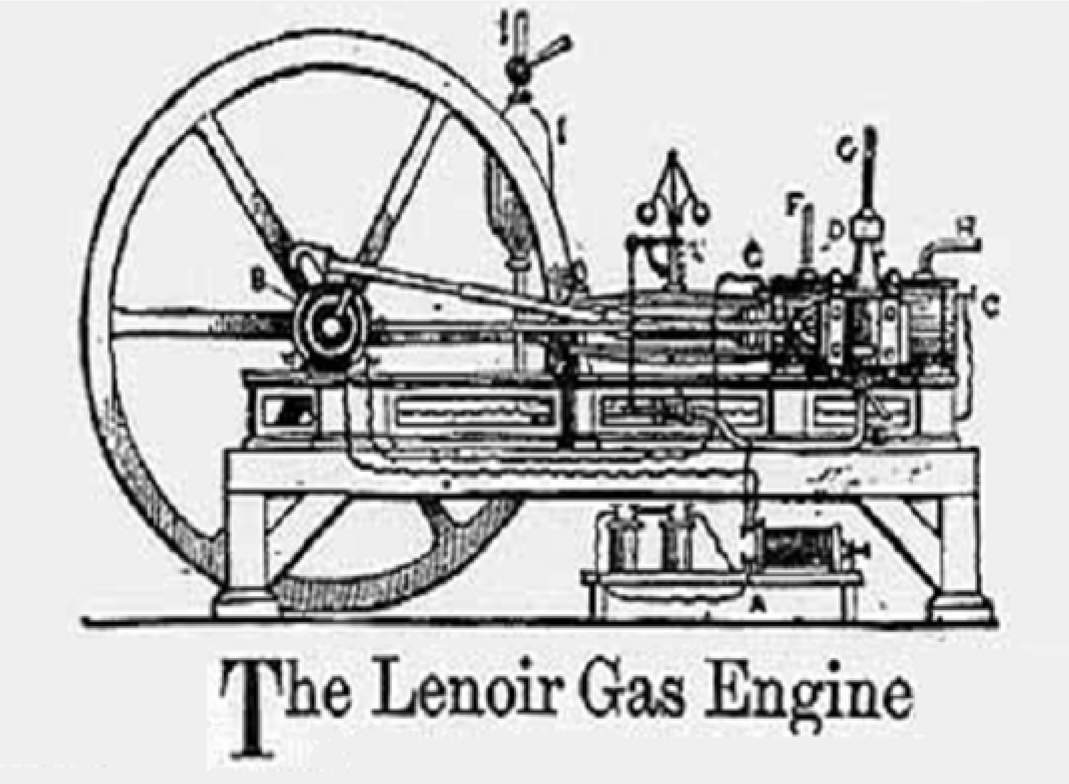
Cecil's Hydrogen Gas Engine Concept (1820)

- 1820, by Rev. Cecil
- Based on hydrogen gas mixed with atmospheric air
  - Ignition by flame
  - Density of exploded gas ≈ 1/6 of atmospheric pressure
  - Atmospheric pressure provides moving force
- Complex, impractical.
- Inspiration for Rube Goldberg.



Lenoir's "Hippomobile" Gas Engine (1860)

- Patented by Jean Joseph Etienne Lenoir in 1860
- First successful internal combustion engine
- Two-stroke gas driven engine

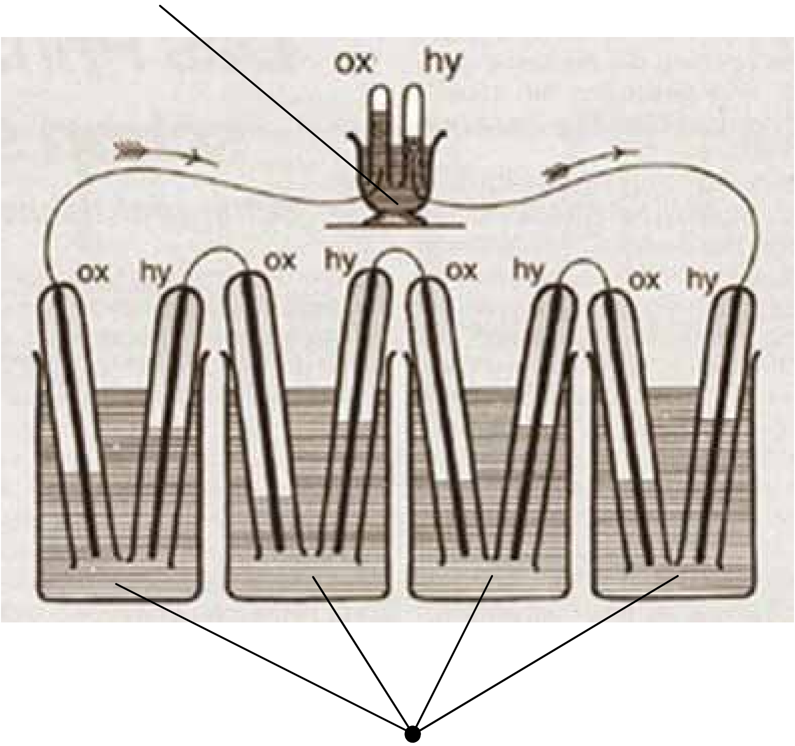


Lenoir's "Hippomobile" (1860)

- Built in 1860 by Lenoir
- 1-Cylinder, horizontal arrangement
- Powered by hydrogen
  - Generated via the electrolysis of water

First Functional Fuel Cell

Water



Sulfuric Acid Solution

- 1839, by Sir William Grove
- Reaction of sulfuric acid solution in lower reservoirs produces water and electricity
- Water in upper reservoir electrolyzed, producing hydrogen and oxygen
  - Upper solution used as a voltmeter

First Fuel Cell Vehicle

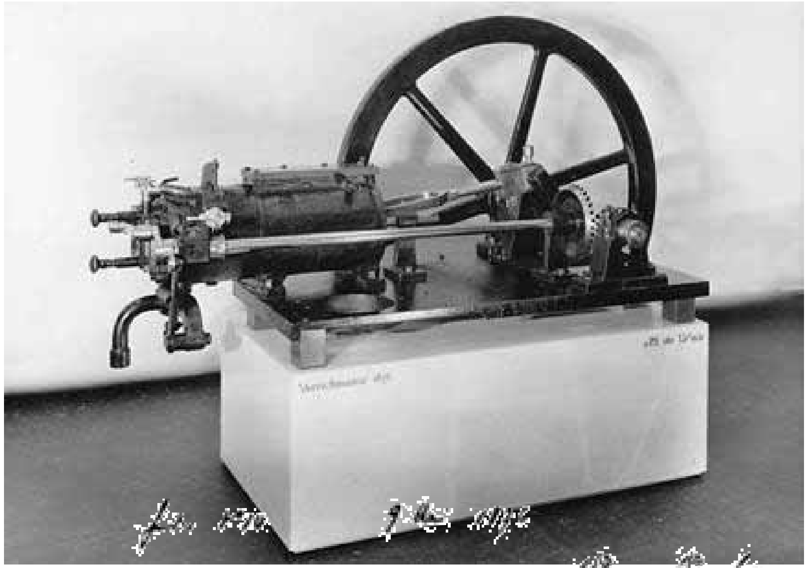
- 1966 Fuel Cell Van ("Electrovan")
- 7,000 pounds
- Fuel
  - Liquid Hydrogen
  - Liquid Oxygen

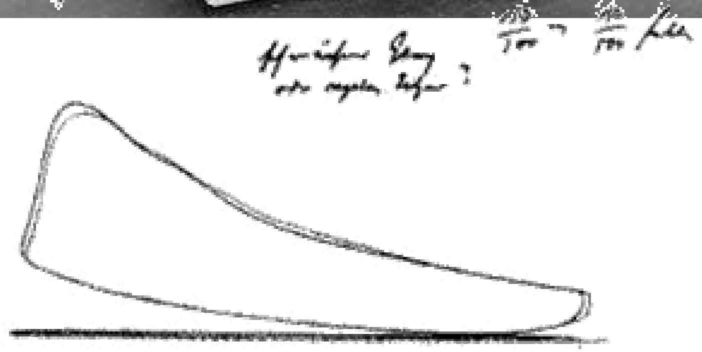
Today's Fuel Cell Vehicles

- Concepts, prototypes, and a limited number in demonstration fleets
- Today's fuel cell powertrain cost ~7 times the price of production ICE engine powertrain

GM's Hy-Wire
Fuel Cell Concept Car

Nicolaus Otto's Four-Stroke Cycle and Engine





- 1876 - four stroke
- engine cycle
  - 3 hp
  - 108/min
- One combustion
- cycle: four-strokes
  - Intake
  - Compression
  - Power
  - Exhaust

First Gasoline-Powered Automobile

- Effective 4 stroke internal combustion gasoline engine invented (1876)
- First gasoline engine used in an automobile
- Built in 1886 by Gottlieb Daimler using Otto’s cycle

Rudolph Diesel's Patent and the First Diesel Engine (1893)

PATENT-URKUNDE

№ 67207

GESETZ v. 7. APRIL 1891

AUF GRUND DER ANGEHEFTETEN BESCHREIBUNG UND ZEICHNUNG IST DURCH BESCHLUSS DES KAISERLICHEN PATENTAMTES

an Rudolf Diesel, Ingenieur, in Berlin

EIN PATENT ERTHEILT WORDEN.

GEGENSTAND DES PATENTES IST:

Arbeitsverfahren und Ausführungsart für Verbrennungskraftmaschinen.

ANFANG DES PATENTES: 28. Februar 1892.

DIE RECHTE UND PFLICHTEN DES PATENTINHABERS SIND DURCH DAS PATENTGESETZ VOM 7. APRIL [illegible] (REICHS-GESETZBLATT FÜR [illegible] SEITE [illegible]) BESTIMMT.

ZU URKUND DER ERTHEILUNG DES PATENTES IST DIESE AUSFERTIGUNG ERFOLGT.

Berlin, den 23. Februar 1893.

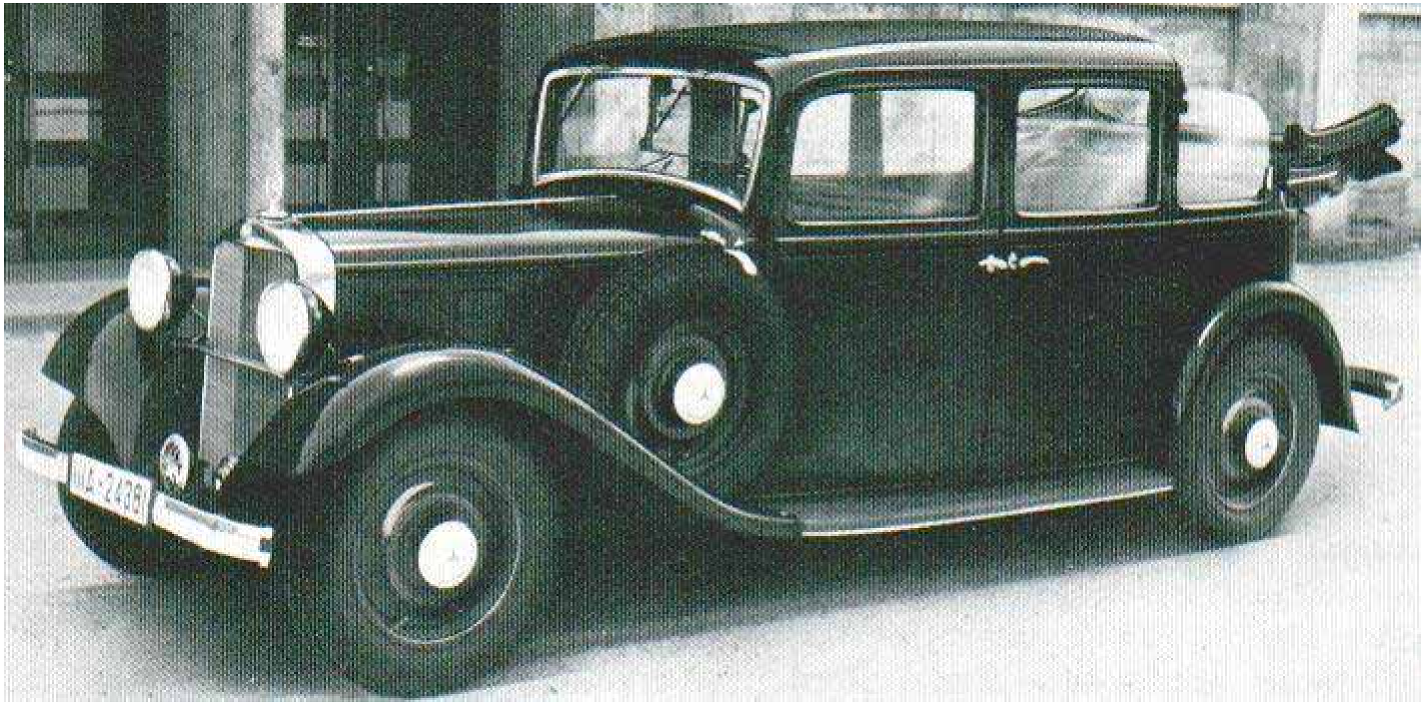
KAISERLICHES PATENTAMT.

Beglaubigt durch [illegible]

Bureau-Vorsteher des Kaiserlichen Patentamtes.

260D (1936)

- World's first diesel passenger car
- Introduced by Mercedes-Benz in 1936



Diesel engines are ***not*** the oldest transportation vehicle engine

Sources of Increases in Diesel Efficiency

- Improved science to the art of engine development
- Sophisticated design tools using computer models
  - Enhanced understanding of engine stresses and temperatures
  - Laser diagnostics in combustion
  - Computer aided manufacturing
  - Rapid prototyping
- Improved manufacturing and quality control
  - Tighter tolerances
  - Improved castings
- Better materials and coatings
- Fuel injection equipment (computer-controlled)
- Increased turbocharger efficiency
  - Variable nozzle geometry
- Emissions aftertreatment

Diesel Engines 21st Century – Surface Transportation

- Displaces steam engines
  - Deep water commercial cargo & cruise ships
    - QE II – built in mid 1950s
      - Steam turbine propulsion: 21 ft/gal fuel
    - Replaced with diesel propulsion & ship's service generators in 1987
      - Diesel engine propulsion: 39 ft/gal fuel
      - Reduced vibrations
  - Inland marine tugs, ferries, fishing boats, pleasure boats

Rapid Transition Steam to Diesel Railroads Starting in 1930s

- **Non-electrified Railroads**
  - 42% improved efficiency
  - Significant emissions reduction
  - Dramatically improved working conditions

Photo by Stanley Goodrick. AC&Y Railroad Historical Society Archives

Diesel, the Only Practical Commercial Engine On- and Off- Highway

- **Long-haul tractor-trailer trucks are almost exclusively diesel**
- **Emissions have been reduced by 88% in the last 12 years**

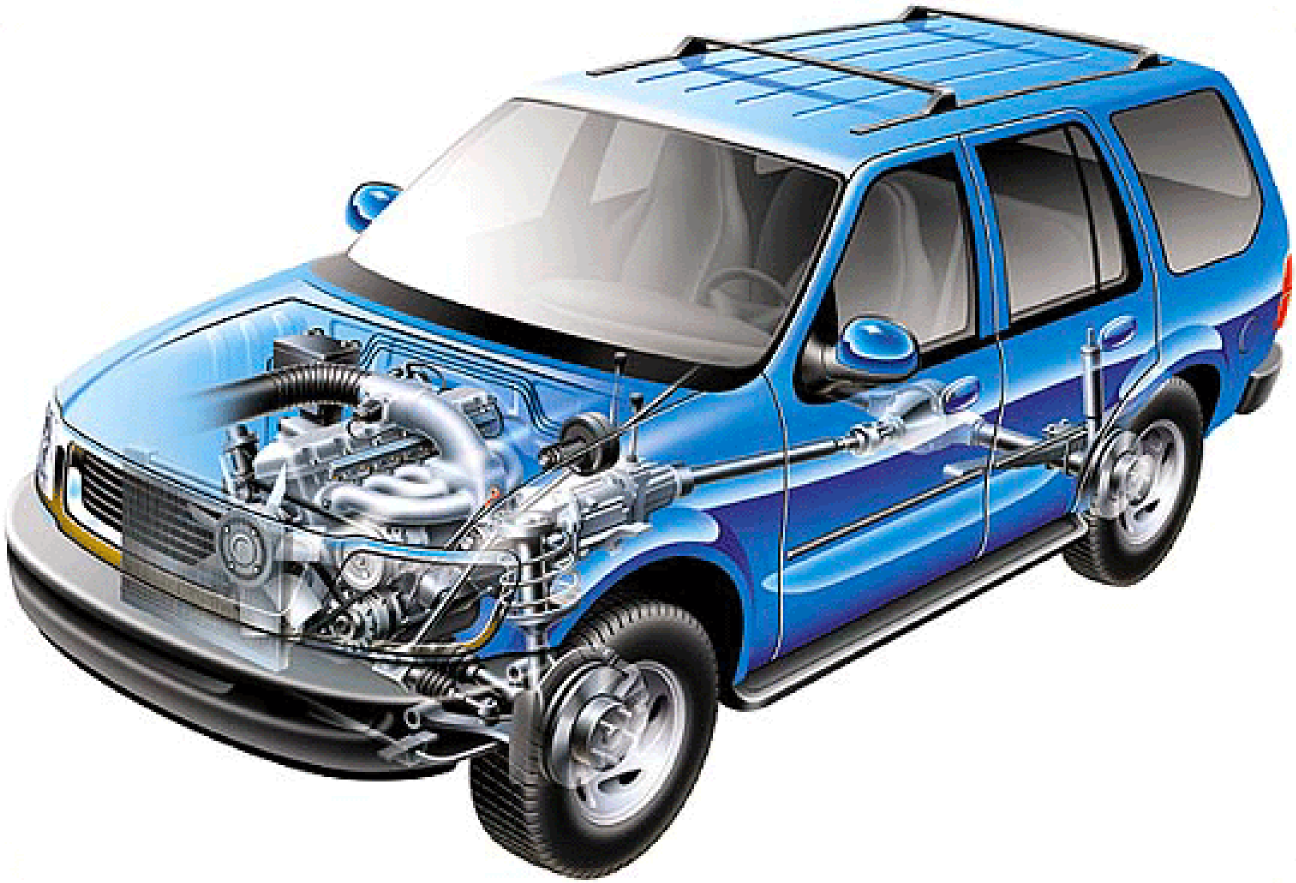
- **Off-road, diesel fuels nearly 100 percent of the off-road equipment used in construction**
- **In less than a decade (1996-2003)**
  - PM reduced by 63%
  - NO_X reduced by 28%

Applications Displacing Gasoline Engines

- Off-highway: construction, garbage, cement mixer, agricultural machinery, and mining
  - 99% diesel
- Class 7 and 8 heavy-duty trucks
  - 1.6 million trucks (99% diesel)
  - Carries 72% of all goods (dollar value)
  - No serious challenge to diesel on the horizon
- Personal vehicles
  - Europe: ~ 50%
  - North America: ~1%

2005 Mercedes Benz and VW: Diesels ~4% of North American Sales

Light-Duty Trucks: Fuel Economy Opportunity For Diesels



Performance of Diesel Engines Developed at Cummins with DOE Support

	City mpg	Highway mpg	Combined mpg	Combined gal/mi	CO_2 Reduction
Dodge Durango					
-Gasoline	12	17	13.8	0.072	--
-Diesel	20.3	25.0	22.1	0.045	--
			+60% Better	37% Reduced	27%
Dodge Ram 1500					
-Gasoline	12	16	13.5	0.074	--
-Diesel	19.8	24.6	21.7	0.046	--
			+61% Better	38% Reduced	28%

Only Near-Term CO_2 Reduction Achievable with Diesel

"The state wants to cut vehicles' output of carbon dioxide by 30 percent over the next decade, limiting a major greenhouse gas through to contribute to global warming."

BY REED SAXON – ASSOCIATED PRESS

California wants to cut vehicle carbon dioxide emissions by 30 percent over the next decade.

California's CO2 Plan Worries Automakers

Cutting Emissions Would Be Costly, Industry Warns

By GREG SCHNEIDER
Washington Post Staff Writer

See **AUTOS**, *E5, Col.1*

California loves cars, with more on the road than anywhere else in the country. But the state where the Beach Boys wrote odes to the "Little Deuce Coupe" and "409" struggles to balance romance with environmental responsibility, and now California regulators have come up with a new clean-air guideline that has automakers howling.

The state wants to cut vehicles' output of carbon dioxide by 30 percent over the next decade, limiting a major greenhouse gas thought to contribute to global warming. It's the first U.S. attempt to address the controversial issue through car emissions, and automakers argue it could boost car and truck pric-

ces nationwide without producing much benefit.

Unlike other engine emissions, carbon dioxide can't be filtered away, so the only way to cut it back is to improve efficiency – in-creasing the distance a car can go on a gallon of gasoline. California regulators estimate that achieving their goal would cost roughly $1,000 per vehicle, but carmakers say that figure is low.

"We would certainly consider it one of the most, if not the most, comprehensive and costly environmental programs that's ever been adop-ted -- not just by California, but by any-one," said John M. Cabaniss Jr., director of envi-ronment and energy at the Association of In-

Climate Shift Threatens California

Two GHG Emission Scenarios

- Fossil fuel use continuing at its present pace
  - Summertime high temperatures could increase by 15°F in some inland cities
- Considerable use of wind and solar power
  - Could push temperatures 4-6 °F

"…rising temperatures could lead to a sevenfold increase in heat-related deaths in Los Angeles and imperil the state's wine and dairy industry."

Proceedings of the National Academy of Sciences, (August 16 2004)

Global Climate Effect on the Maine Lobster Industry

Not a lot of lobster

Global warming blamed

By Jeff Donn
ASSOCIATED PRESS

FRIENDSHIP, Maine — It's summer on Maine's coast, but this morning, Philip Bramhall pulls on a hooded fleece shell with his rubber overalls to heave 50-pound lobster traps around his boat's deck.

He doesn't mind the early chill and wet fog. Lobsters like cold, and Mr. Bramhall likes lobsters.

Maine's lobstermen have been hauling up phenomenal numbers for almost 15 years. Their 62.3 million pounds in 2002 set a record — triple the typical catch during the 1980s. That's more than $200 million worth of lobster and by far the dominant share of the Northeast's most valuable fishery. But can it last?

Starting in the late 1990s, in the southern reaches of its near-shore commercial range, the big-clawed American lobster — prized for its delicate, sweet flesh — has been withering at an alarming rate from New York state to Massachusetts.

Government biologists have said the lobster is overfished off the Northeast, but that doesn't account for Maine's extravagant abundance. Researchers in various localities have blamed the trouble on diseases, pollutants and predators. But that fails to explain any larger pattern.

In recent months, however, a consensus has emerged among scientists who blame the shift on global warming.

The theory holds that warming is already killing off the American lobster in its southern near-shore range, where it lives near its heat tolerance. In Maine, where it is well within its comfort zone, more warmth — up to a point — might be making it proliferate.

If temperatures rise too high, though, even Maine ultimately might become less hospitable to lobsters, some researchers say. Last year's state catch fell back almost 14 percent to 53.9 million pounds.

"We're hoping our cold water will keep it to the south, because so much of our economy is dependent on lobstering," says Pat White, chief executive officer of the Maine Lobstermen's Association. "If it hit us, it'd be a disaster."

Five generations of Bramhalls have fished lobsters in Maine. Since about 1990, times have been fat for Friendship and much of Maine's coastline. Today, most families in this village of about 1,200 live off lobsters. They are fishermen, dealers, trap makers, boat builders, marine outfitters. Potentially lucrative lobstering tempts teenagers from high school.

Mr. Bramhall is grossing about $150,000 during the April-to-January lobstering season, almost double his former business. He has added a family room and two-car garage to his house. He has bought three new pickups and a camper. He intends to build a bigger boat.

He shrugs off government biologists who predict a lobster drop-off, based on what he calls arcane calculations concocted in stuffy offices.

"They don't see what we see out here when we haul up a trap. You might see 25 to 30 small lobsters in it," he says.

The first signs of distress in the American lobster industry appeared in the western Long Island Sound near New York City in fall 1999 and slowly spread north. Boats began pulling up more and more lobsters with bumpy black scars from a bacterial disease that could bore right through their shells. They were alive, but no one would eat the nasty-looking creatures.

By 2000, the catch off eastern Connecticut and Rhode Island was crashing. The take in Massachusetts began to shrink the next year and further north in New Hampshire a year later.

Scientists and lobstermen searched for a culprit. On western Long Island Sound, it turned out the lobsters were infected with a parasitic amoeba.

Suspicion turned on mosquito pesticides sprayed to control West Nile virus. About 1,100 lobstermen collectively sued pesticide makers, claiming $200 million in losses. The case awaits trial. Elsewhere, chlorine from sewage plants fell under suspicion.

Scientists also have found more lobster predators, like striped bass, in waters south of Maine. Maybe they were devouring more lobsters, but that didn't account for the outbreaks of disease.

By official standards, lobstermen are overfishing Northeastern waters. They are leaving too few lobsters to breed later generations, even in Maine, according to the calculations of government biologists. Some predict a drastic decline in Maine.

For the moment, though, something seems to be shielding Maine. The more southern a state, the more its catch has dwindled, according to an Associated Press analysis of the latest complete state data. New York's lobster take collapsed by 75 percent from 1999 to 2002. Moving progressively northward, the drops attenuate: Connecticut, 59 percent; Rhode Island, 33 percent; Massachusetts, 14 percent; New Hampshire, 3 percent. Government estimates of the lobster population nose-dived during the same period.

Two summers ago, yet another lobster disease turned up. Orange grit was clogging the gills of lobsters around eastern Long Island Sound. Under study, it proved to be calcinosis.

Alistair Dove, at the State University of New York at Stony Brook, got to thinking about what could drive a lobster's metabolism and, by extension, cause such a metabolic disease.

"That was the first time we thought of temperature," he says.

If overheating was making the lobsters sick, excess acid should accumulate in their blood, like a human sprinter building up acid in his muscles. Mr. Dove's research team began testing lobsters for the telltale acid. Last September, they found it.

Maybe cold-blooded lobsters in their southernmost range have been stressed by a slow rise in water temperature, Mr. Dove's team theorized. Recent seasonal heat spikes, starting from the higher norms, might have overwhelmed many lobsters.

In Maine, by contrast, warmth likely has accelerated their life cycle, yielding more adults and more active ones. They would be easier to find and trap.

During the five years ending in 2002, the surface waters off Boston were more than 2 degrees higher than their historical averages, according to government data. In recent summers, the temperatures in some waters off southern New England have increased into the low 70s, the upper limit of what lobsters can tolerate, researchers say.

This past spring, about 60 lobster researchers brainstormed in Groton, Conn. They agreed that, perhaps more than any other single factor, warming water seems to account for the lobster's decline, several participants say.

Some fear that if temperatures keep pushing upward, even Maine's fishery will sink. Shell disease already has begun to appear there.

"What is possible for us to control?" asks Josef Idoine, a federal lobster biologist. "By and large, what you're left with is the harvesting rate."

So, many managers argue for tighter fishing rules, even if there is no guarantee that they will do enough.

Business is booming for Maine lobstermen like Ben Lash, but is falling off in southern waters.

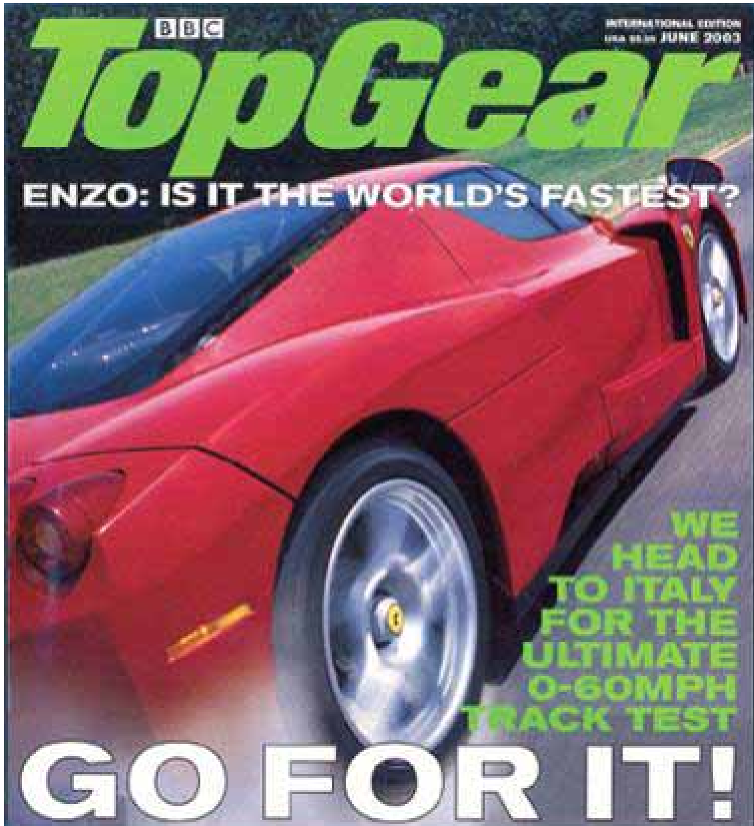
Associated Press

"…about 60 lobster researchers brainstormed in Groton, Conn. They agreed that…warming water seems to account for the lobster's decline.

"…Last year's state (Maine's) catch fell back almost 14% to 53.9 Million pounds.

The Washington Times, August 24 2004

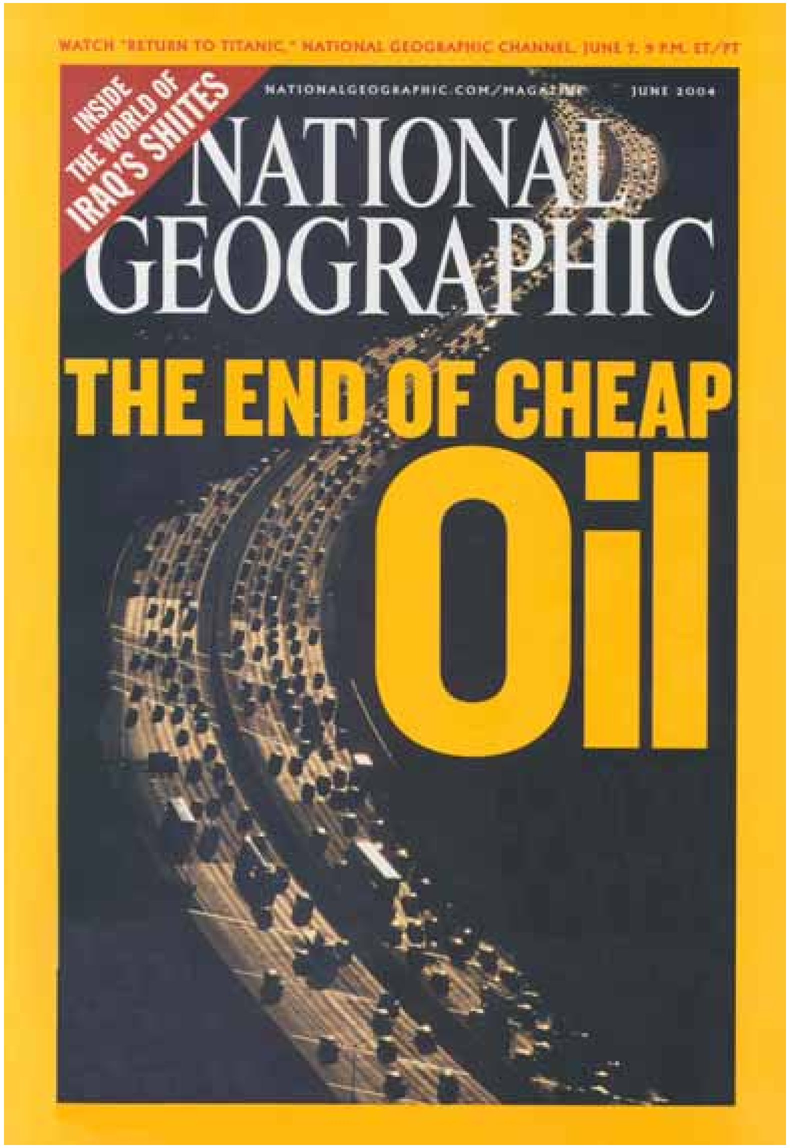
Is the Ferrari Enzo the World's Fastest?



PERFORMANCE

	Ferrari Enzo *12 Cylinder Gasoline Engine*	**Banks Sidewinder** *6 Cylinder Diesel Engine*
Top Speed	217 mph (estimated)	222.139 mph (measured)
Fuel Economy	8-12 MPG	21.2 MPG

Petroleum Market Forecast



The Washington Post
August 5, 2004

Prices for Oil Head Back to Record Levels

Saudi Call for More Output Does Not Impress Markets

By JONATHAN WEISMAN
Washington Post Staff Writer

Oil prices climbed back into record territory yesterday after energy traders shrugged off pledges by Saudi Arabia to increase production and focused instead on OPEC discord and the shutdown of a major oil platform in the Gulf of Mexico.

Gasoline prices, meanwhile, continued their steady upward march. Pump prices for regular unleaded gasoline increased 4.7 cents in the past week, to a national average price of $2.064 a gallon, the Energy Department's Energy Information Administration said yesterday. ,

Regular unleaded prices rose nearly a penny in Maryland to an average of $2.015, while Virginia prices climbed 1 cent to $1.934, according to the AAA motor club survey. Experts said it's likely gasoline prices will keep rising as the United States heads into the vacation-heavy summer driving season, re-

"Experts said it's likely gasoline prices will keep rising…"

Newsweek
August 16, 2004

Jane Bryant Quinn

Gas Guzzlers' Shock Therapy

MY FELLOW AMERICANS, DROP THE FANTASY that we'll return to cheap gasoline, and pump it for as long as our withered hands can steer an SUV. As the prophet saith, the end is nigh. Demand for oil is running high—in fact, we're gobbling up the stuff. But world production grew by only 0.6 percent a year for the past five years. At some point, supplies will shrink, not grow.

The two oilmen in the White House maintain that we can drill our way out of this hole. George W. Bush is campaigning on subsidies for more oil production at home, especially in the Arctic. John Kerry says he'd invest in alternative fuels, raise mileage standards for cars and SUVs, and subsidize energy efficiency. For their part, consumers don't want to hear that oil could run out. That Escalade in the showroom just looks too good.

Am I crying wolf? If so, I'm in the company of some pretty big guns in the oil biz—geologists, merchant bankers, analysts and petroleum engineers. They note that the major companies aren't building new U.S. refineries, investing in drilling or enlarging the tanker fleet—suggesting that they don't expect much new oil to appear. Saudi reserves, which the world depends on to fill every energy gap, remain a state secret; outsiders wonder how big they really are.

Princeton geology professor emeritus Kenneth Deffeyes, who's writing a book due in 2005 called "Beyond Oil," waggishly names an Armageddon date: "World oil production will reach its ultimate peak on Thanksgiving Day 2005," he says. Then the long, slow decline begins (for a fuller discussion, see oilpeak.com).

Terrorism is catching the blame for pushing the price of September oil futures to a record $44.41 a barrel last week. In fact, "the war has very little to do with it," says energy consultant Philip Verleger. Prices are rising under the pressure of soaring demand for gasoline. Markets are catching on to the tightening of supplies, even if civilians aren't.

None of this means lines at the gas pumps or gas holding firm at $2 a gallon. Oil prices are cyclical, says oil analyst Matt Conlan at Weeden & Co. They'll peak, then drop, bottom out and rise again. But each cycle will start and end at a higher price.

As you might expect, a campful of critics call this "peak oil" theory nuts. They expect new finds or technologies to keep the black stuff flowing. And maybe they're right. But what if they're wrong? A permanent shrinkage in supplies would so severely damage today's oil-based economy that it makes no sense to wait and see. We need energy options, just in case. If shortages don't develop, we'd still be ahead of the game, with more diverse and cheaper sources of energy for future growth.

What might we turn to? The easiest would be efficient diesel cars, Deffeyes

One expert has picked an Armageddon date for the peak of oil production: Thanksgiving 2005. The slow decline in world supplies will start then.

says. They use oil, but are capable of getting more than 90 miles to the gallon. Two little problems: diesels smell bad and pollute the air. But they also can run on a mixture that includes soybean oil, which smells more like salad.

Greenies are eying "hybrid" cars. They run on gasoline but store electrical energy when you step on the brakes. At slower speeds, the cars run on electricity alone (and no, you don't have to plug them in). Consumers Union clocked them at 36 to 51 miles per gallon. The 2004 Toyota Prius hatchback costs up to $1,850 more than conventional models, with some dealers charging over the sticker price. If you drive 15,000 miles a year at an average price of $1.55 a gallon, it takes less than six years to make up that extra cost, says Jim Kliesch of the American Council for an Energy-Efficient Economy. Buyers also get a $1,500 write-off on their federal taxes this year. Some states offer write-offs, too.

Wind technology has already shown its worth. If long-armed windmills were driving electric utilities, there'd be more oil for transportation: planes, trucks and cars.

What's more, we have an enormous untapped resource—namely, conservation. Vice President Dick Cheney famously dissed it in 2001 as no more than a "personal virtue"—warm, fuzzy and essentially useless.

He has blinders on. Conservation, in the form of superefficient energy use, is the fastest-growing and cheapest "source" of energy in the United States. When California's energy prices soared in 2002, the state cut its usage by 14 percent (adjusted for economic growth)—avoiding the need for hundreds of new power plants. Some 40 percent of the nation's energy needs since 1975 have been met purely through using energy more intelligently, says Amory Lovins of the Rocky Mountain Institute, which tackles sustainable-energy projects.

Bush has spectacularly backed off efficiency programs, says the ACEEE. He tried to reduce the new energy-conservation standards for air conditioners. His proposed 2004 budget all but wiped out spending to improve efficiency (Congress restored some of the cuts). The 2005 budget chops again. Required new-appliance standards haven't been issued.

Tying our future to oil is a dangerous game. Dependency on crude is one of the things that enmeshes us in the explosive conflict of the Middle East at a cost, so far, of 1,051 lives. I wish that Iraq's only export were nuts and dates. We'll be engaged in that part of the world until oil doesn't matter anyway.

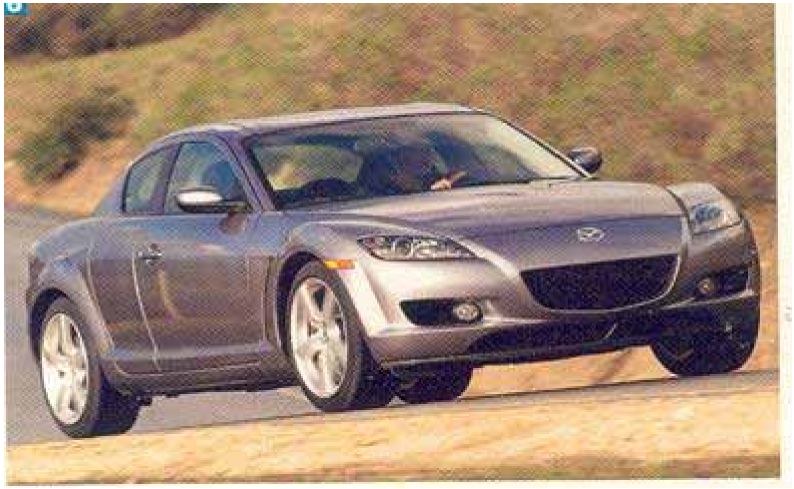
Reporter associate: TEMMA EHRENFELD

"One expert has picked an Armageddon date for the peak of oil production: Thanksgiving 2005. The slow decline in world supplies will start then."

Diverse Gaseous and Liquid State Fuels

- Petroleum
  - gasoline
  - diesel
- Hydrogen
  - Tolerant of impurities
- Hydrogen-enriched
- Bio-fuels
- Gas-to-liquids
- Oil sands
- Natural gas
- Coal-derived
- Shale-derived

ICE Operating on Hydrogen Fuel

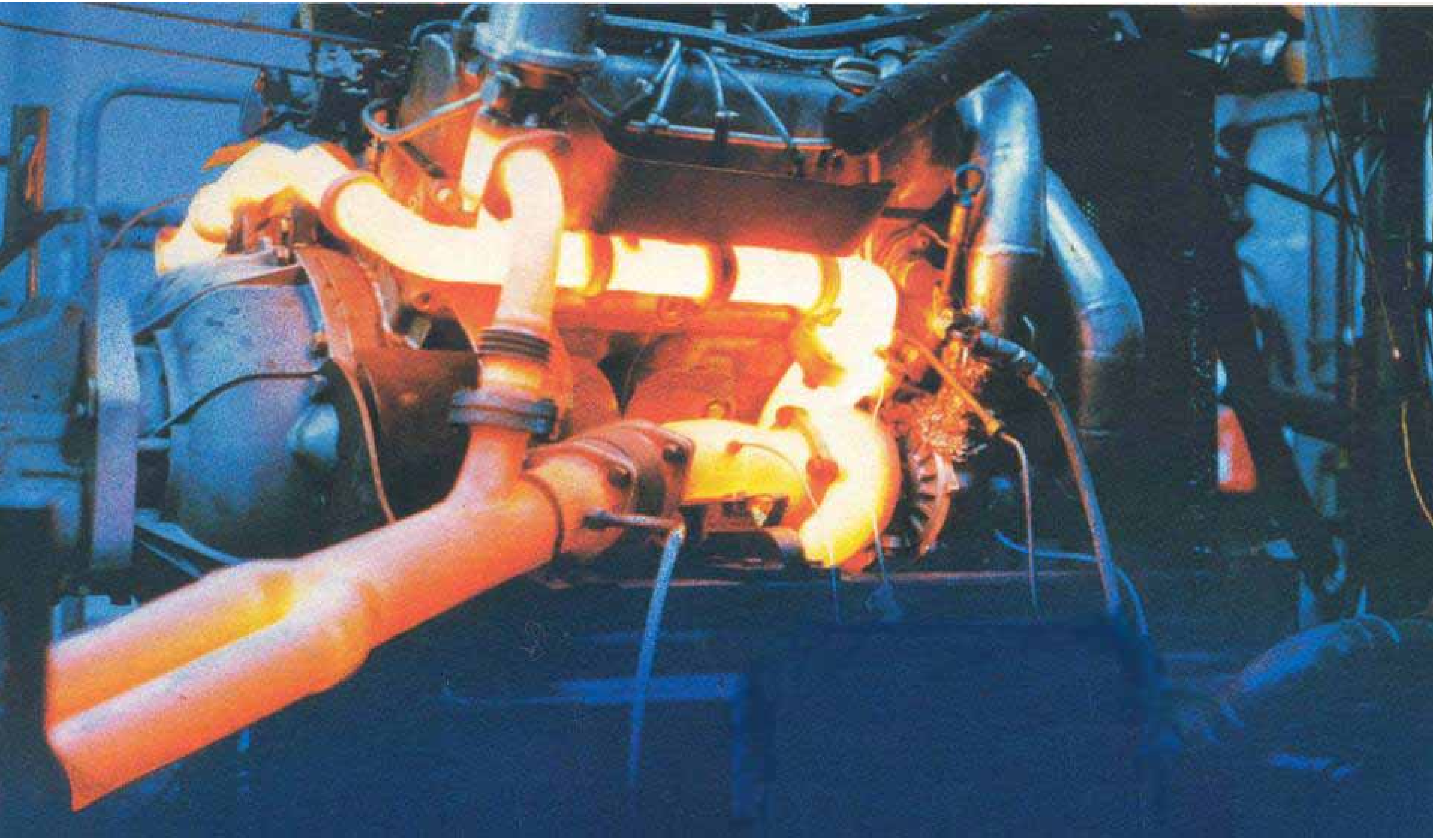


- As hydrogen becomes available
- Diesel or SI gasoline engines could be modified to operate on hydrogen
  - Help enhance commercial aspects of the hydrogen infrastructure

Potential Improvements for 60% Efficient Diesel Engines in 2014

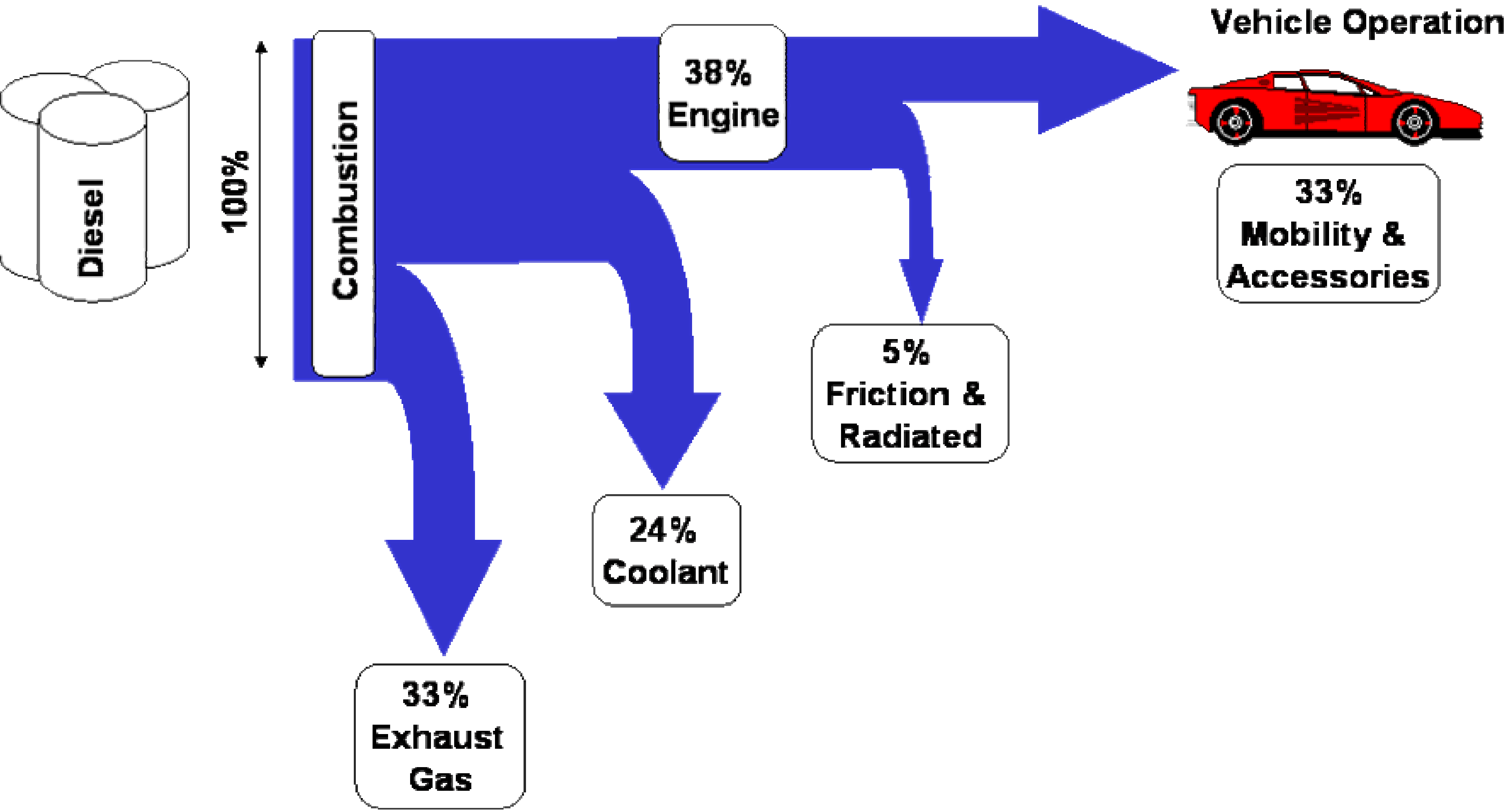
- Improved fuel injection equipment
  - Most of emission reduction in-cylinder
  - Rate shaping of injection charge
  - Advanced microcomputer controls
    - Integrated with aftertreatment
- Reduced weight
  - Moving parts
  - Aluminum block (vehicle mpg)
- Variable-nozzle sequential turbochargers
- Waste heat utilization
  - Turbocompounding
  - High efficiency thermoelectrics
- More electric trucks (belt-less engine)
- Advanced motor/alternator starter damper (ISAD)

Diesel Engine Waste Heat Energy



U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

Typical Fuel Energy Path in Diesel-Fueled Personal Vehicle

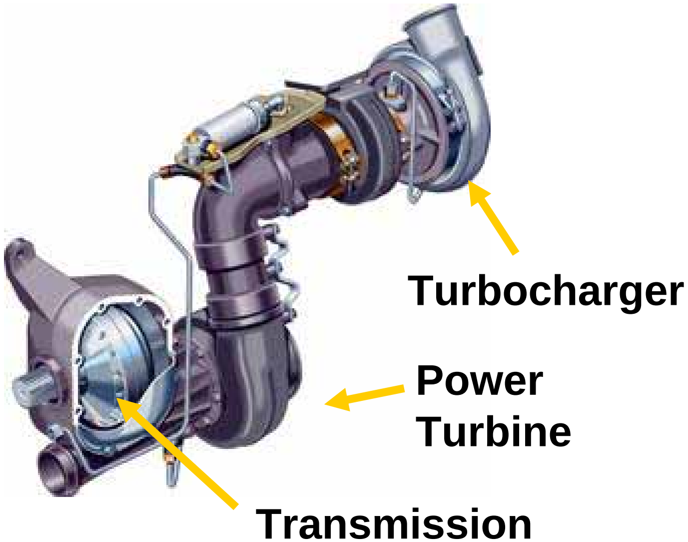


Waste Heat Accounts for 60% of the Diesel Fuel Energy

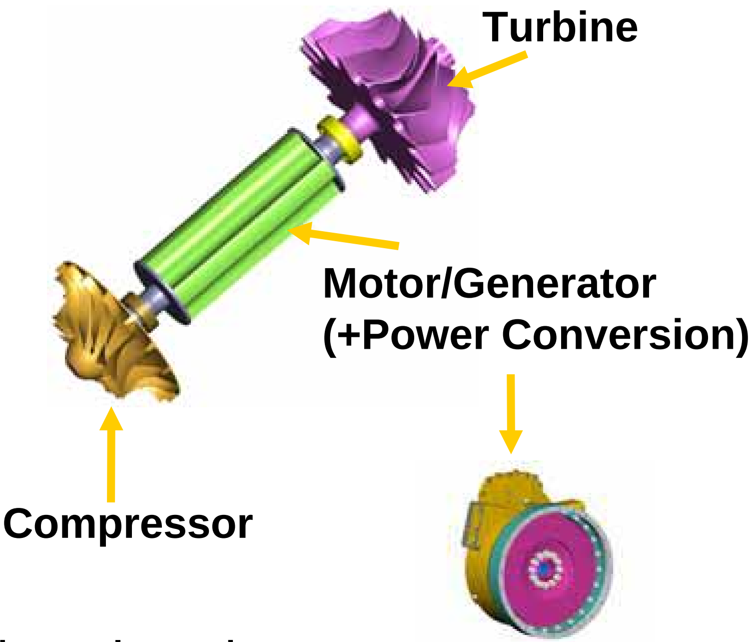
- Diesel engine waste heat recovery
  - Turbocompound
    - Mechanical
    - Electrical
  - High-efficiency thermoelectrics - ΔT's
    - Radiator
    - Lube oil sump
    - Exhaust gas
    - EGR loop
    - Turbocharger discharge
    - Braking
  - Belt-less or more electric engine
  - Integrated starter, alternator/motor, damper (ISAD)
- Major contribution …… 60% efficient diesel

Turbocompounding

Mechanical System

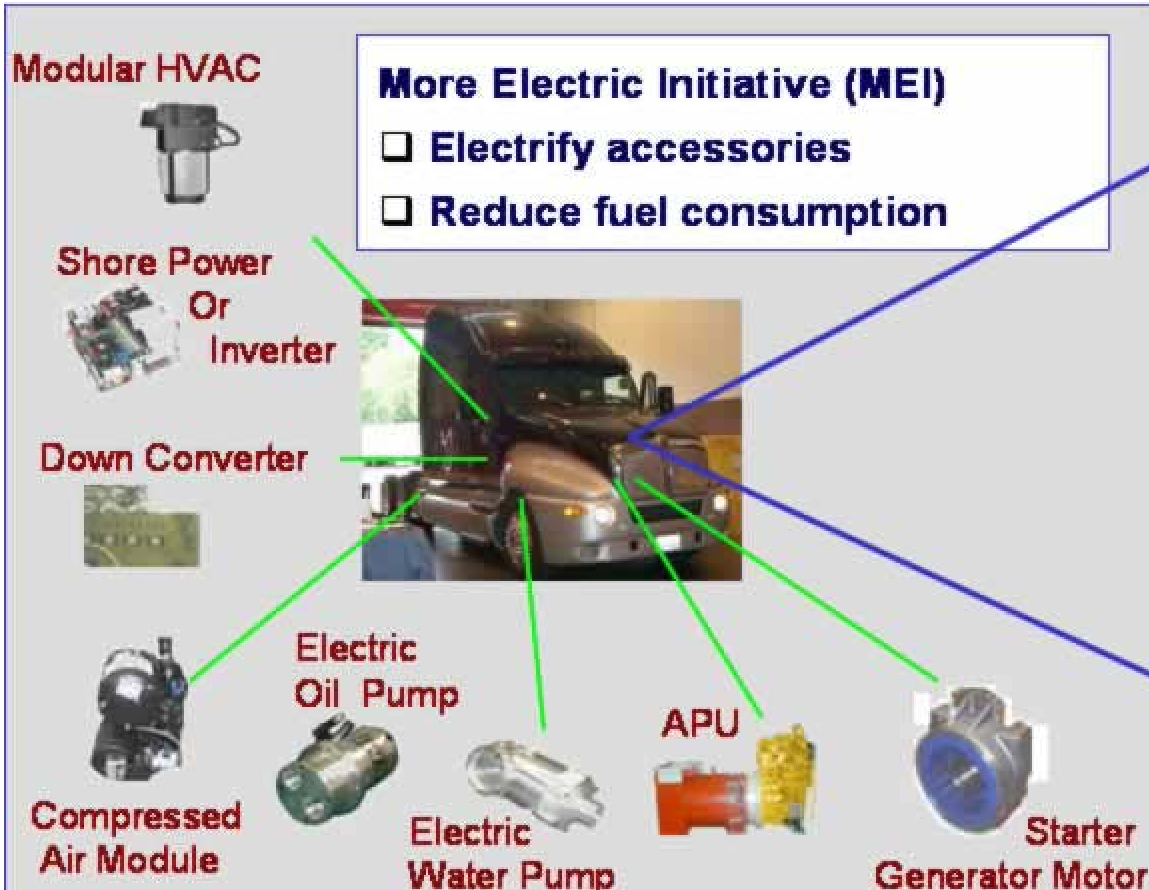


Electrical System



- ETC system has been designed and analyzed
- 5% - 10% fuel economy improvement potential
- Opportunity for reduced emissions and improved driveability

Diesel Engine Waste Heat Recovery Utilizing Electric Turbocompound Technology

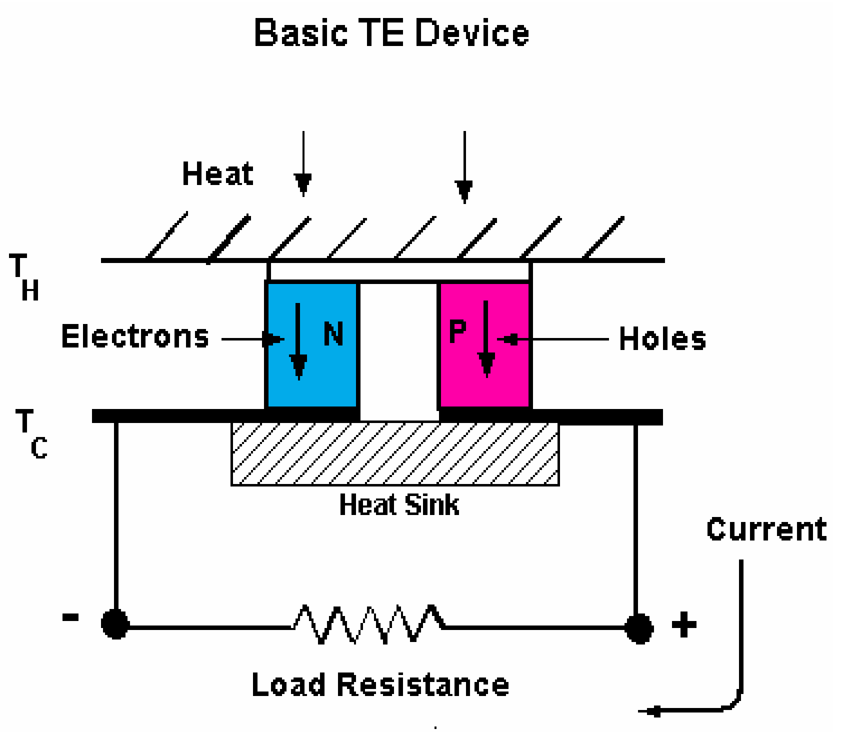


Electric Turbocompound Turbocharger

- ❑ Enables 5 to 10% Reduction in Fuel Consumption
- ❑ Integrated into MEI Truck

Thermoelectric (TE) Energy Conversion

Hot Side ("Waste Heat")



Cold side

Waste heat >> Electricity

Heat-to-electricity conversion efficiency depends on a figure of merit, Z, that is material-specific:

$Z = S^2\sigma/k$

S = Seebeck Coeff = dV/dT

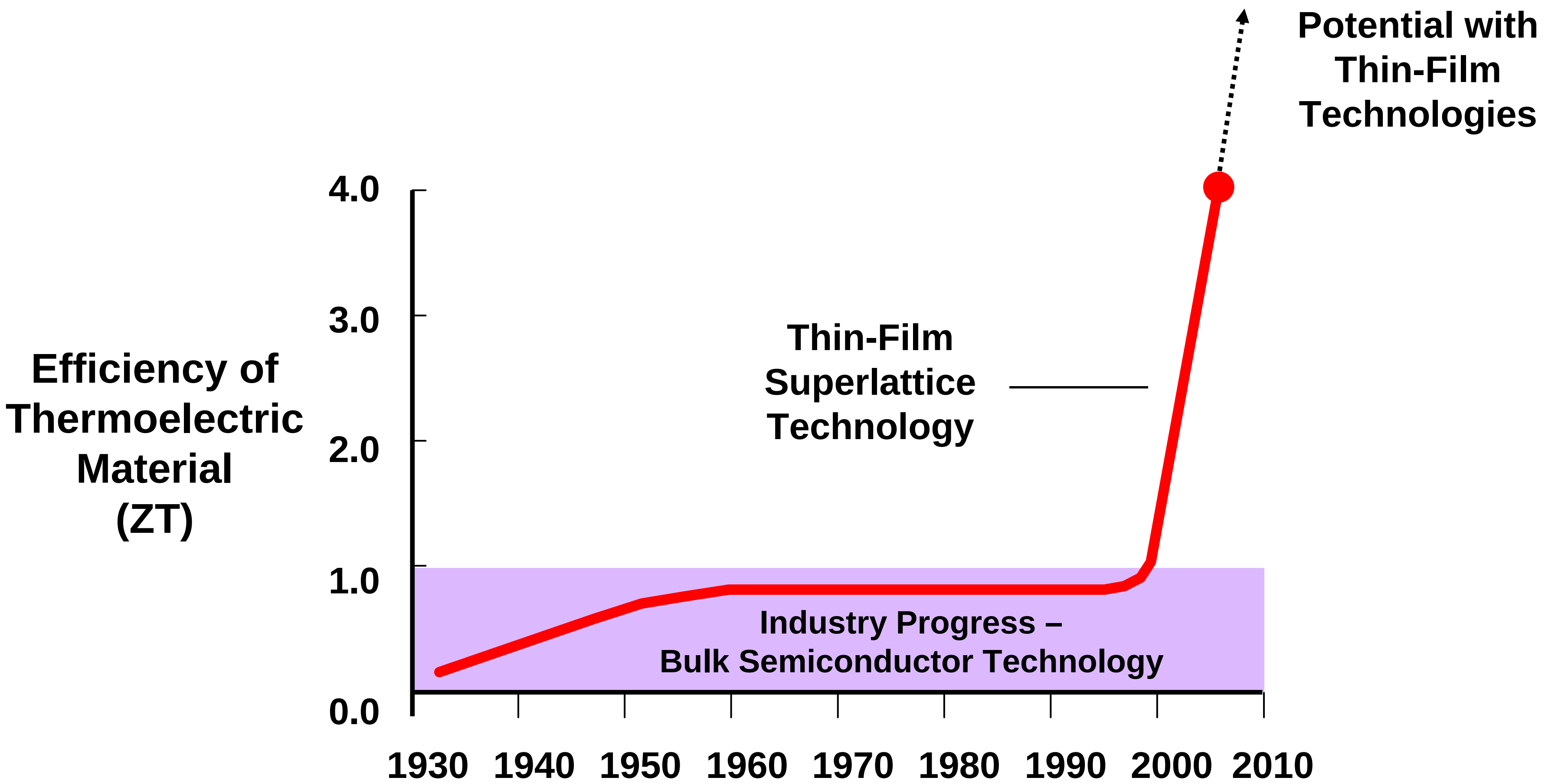
σ = Electrical Conductivity

k = Thermal Conductivity

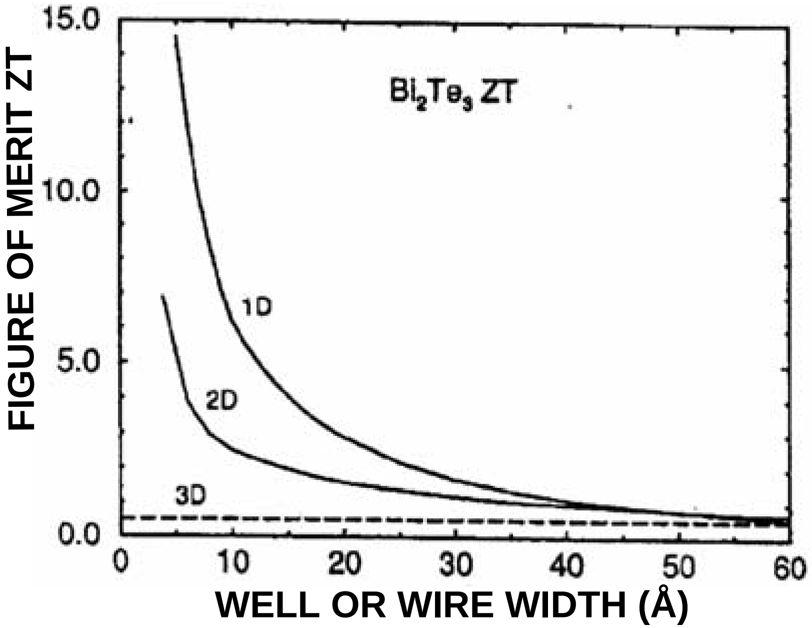
$$\eta = \frac{T_{hot} - T_{cold}}{T_{hot}} * \frac{\sqrt{1 + ZT_{avg}} - 1}{\sqrt{1 + ZT_{avg}} + \frac{T_{cold}}{T_{hot}}}$$

Carnot efficiency.

Recent Breakthrough in Efficiency of TE Materials



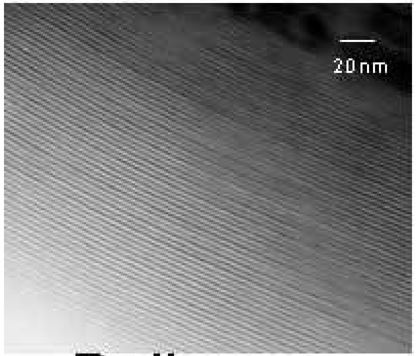
Prediction of Quantum Confinement Effects in Low-D Systems



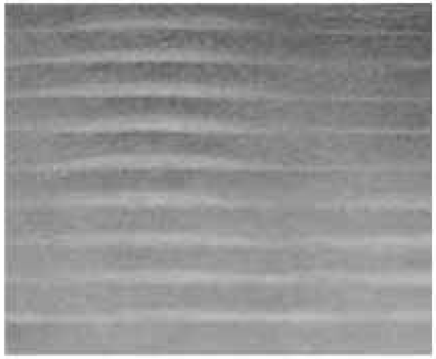
Note: Conduction is assumed to be along the extended dimension

2D, 3D: Hicks and Dresselhaus, Phys. Rev. B47 (1993), p. 12727-31

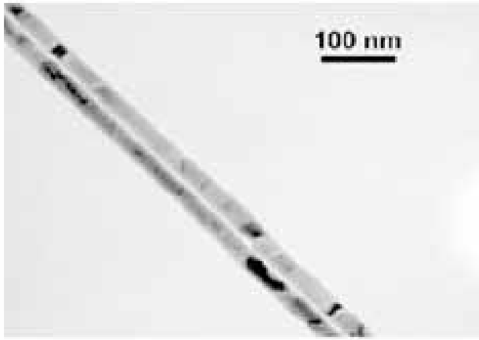
1D: Hicks and Dresselhaus, Phys. Rev. B47 (1993), p. 16631-34



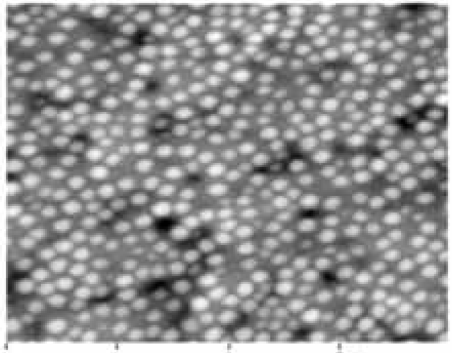
Bulk



Superlattice 2D

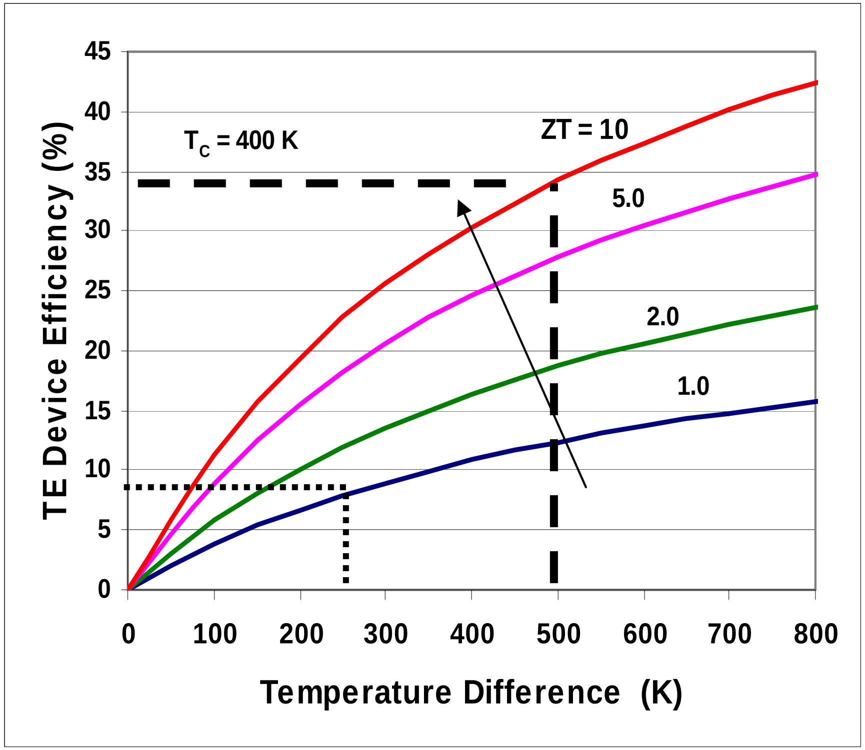


Nanowire 1D



Quantum Dots 0D

Thermoelectric (TE) Energy Conversion



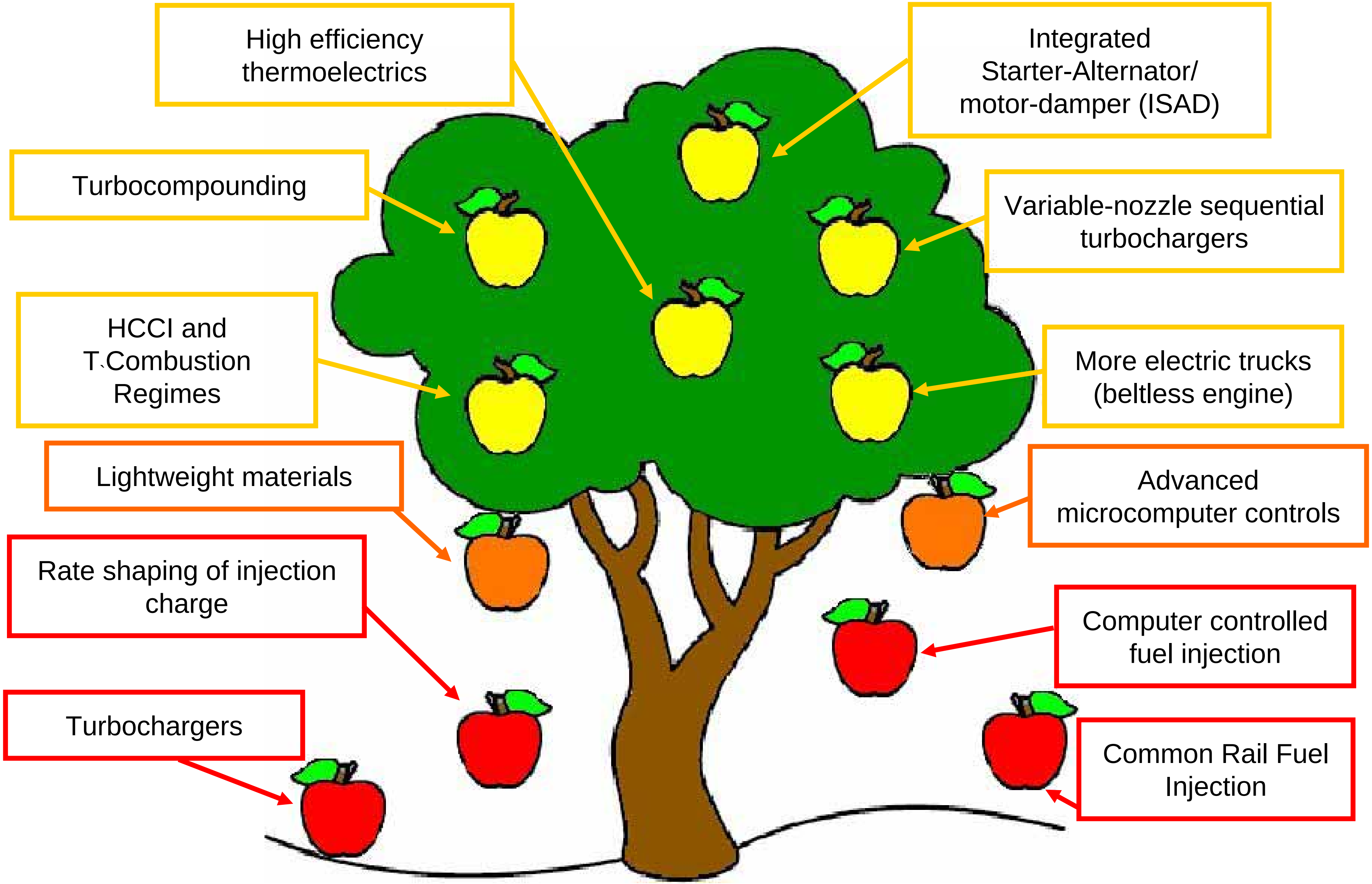
For a given ΔT, higher the ZT, higher the heat-to-electric conversion efficiency

If ZT of 10 can be achieved, a theoretical conversion efficiency of ~35% is possible for ΔT of ~500C

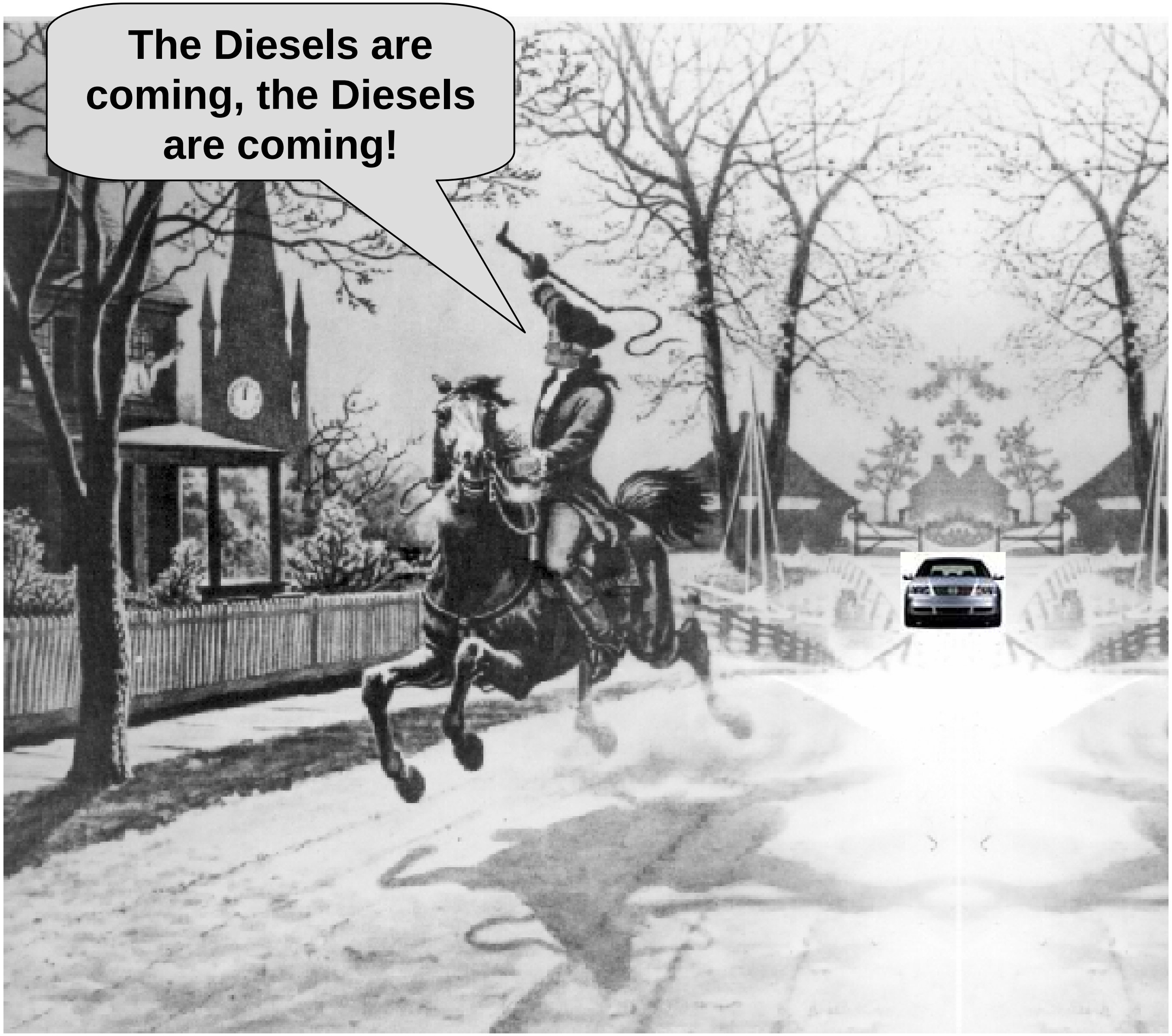
Summary

- North American personal vehicle market factors
  - Emission standard compliance challenge
    - Low sulfur fuel
    - Integrated in-cylinder and aftertreatment
  - Fuels availability and costs
- Cost of owning and operating
  - CO_2 legislation could accelerate diesel sales
- Current diesel efficiency ~ 38%
- Potential diesel efficiency (by 2014) ~ 60%
  - Waste heat utilization major contribution
- Comparison of high efficiency, clean diesels with other technologies should be on a comparable time-frame basis

Technology Tree Enabling a 60% Efficient Diesel Engine



Paul Revere Gets It Right!



Chronology of Diesel Engine Development

Year	Event
1893	Rudolph Diesel's paper ("the theory and construction of a rational heat engines"), Diesel awarded the patent and built the first compression-ignition engine
1905	Alfred Buchi patent for practical turbocharger
1915	Buchi's prototype: first turbocharged diesel engine
1927	Robert Bosch developed the first fuel injection system, allowing metering of fuel
1957	First turbocharged diesel heavy-duty truck engine
	First production high-pressure diesel FIE
1980's-Present	Rate shaping with FIE, including pilot injection (reduced noise and NO_x)
	Emission reduction aftertreatment
1983	First electronic diesel control (EDC)
1990's	Computer controlled FIE pioneered by DDC
Late- 1990's to Mid- 2000's	HCCI and low-temperature regime combustion advances
	Waste heat utilization: Turbocompounding and bulk semiconductor thermoelectrics
	Beltless enguines or more electric trucks
	Integrated starter, alternator/motor, damper (ISAD) development
1999	Common rail FIE for passenger cars
2004	DOE contract for high efficiency thermoelectric waste heat recovery
2005	BMW introduces electric water pump (Series 5)