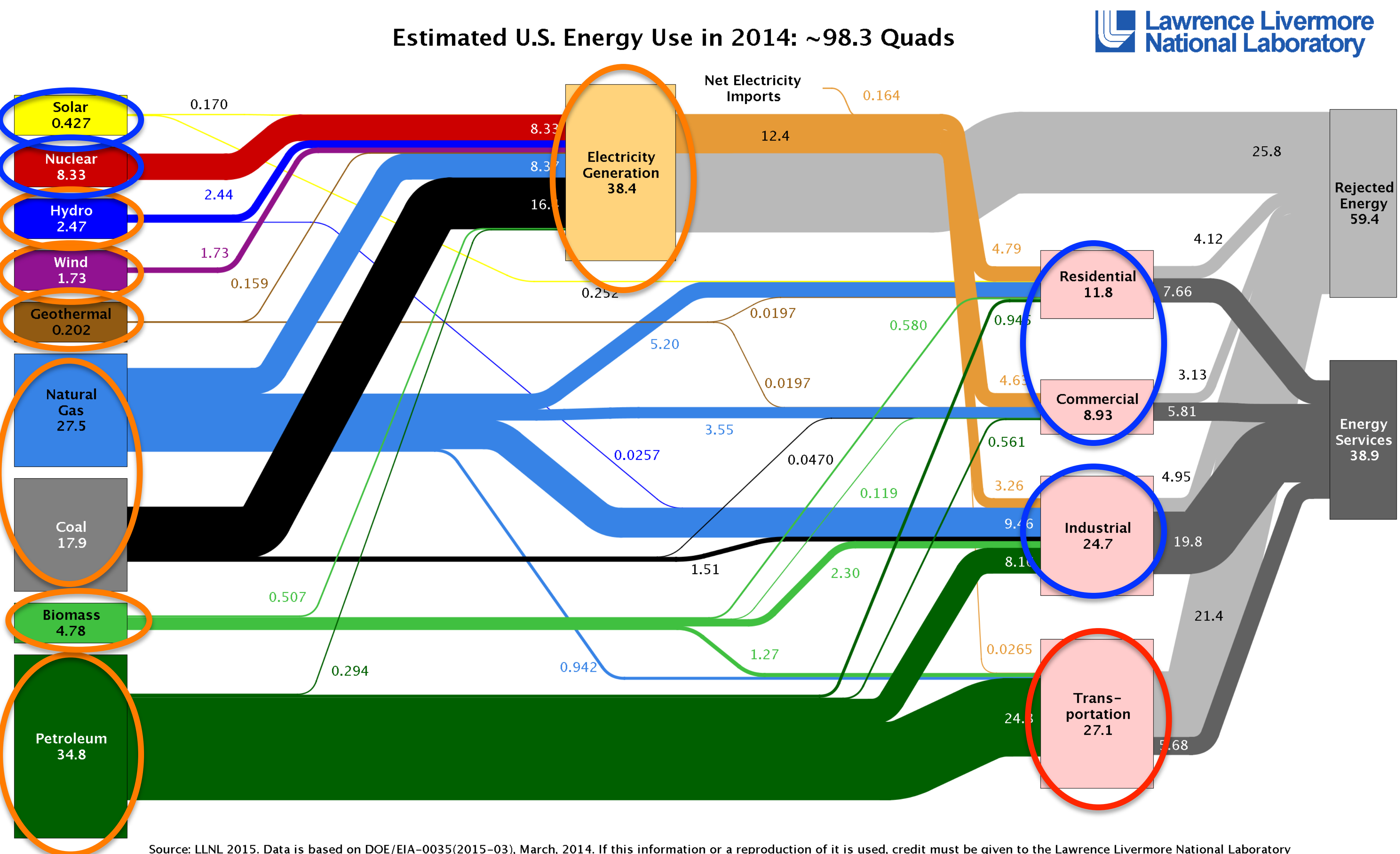
GEOS 24705 / ENST 24705 / ENSC 21100

Lecture 18

Transportation & engines

Oil is now 1/3 of U.S. primary energy use

from LLNL, in quads/yr : 1 Q / yr ~ 10^{18} J / yr ~ 30 GW



Source: LLNL 2015. Data is based on DOE/EIA-0035(2015-03), March, 2014. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential and commercial sectors 80% for the industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

Why are liquid fuels so important?

Why are they the primary transportation fuel ?

1. Allow **internal combustion engine** which is intrinsically lighter than external combustion engine (W/kg)

2. Fuel has high **mass energy density** so range is high (J/kg)

3. Fuel has high **volume energy density** so again, easy to bring enough to get high range (J/m^3)

Reciprocating internal combustion engines

…. Power nearly everything that runs on liquid fuel

…. Consume nearly all oil used

…. Make up 1/3 of U.S. primary energy consumption

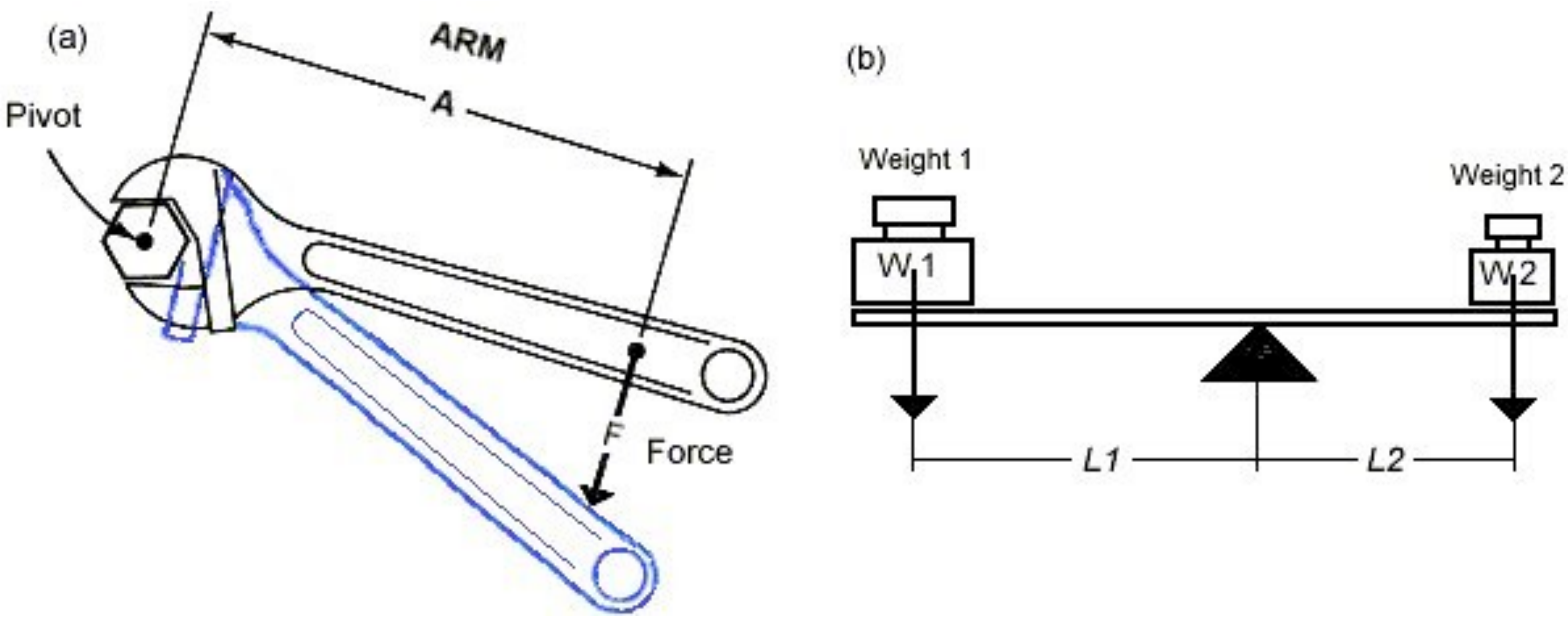
Automobiles and trucks
Motorcycles
Locomotives
Boat engines
Propeller airplanes
Diesel generators
Riding lawnmowers
Outboard motors
Chainsaws (the non-electric kind)
Weed-whackers

Uses: things that need to be mobile, where power-to-mass matters

Torque = “turning force”

Your ability to turn something depends not just on the force you apply but on the lever arm you have

Torque = force x distance   units of energy



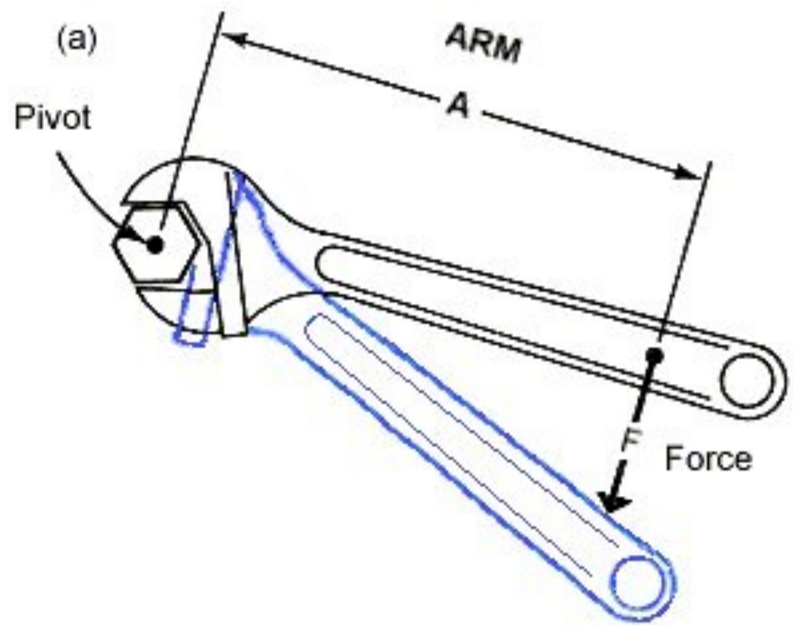
Power = energy/time

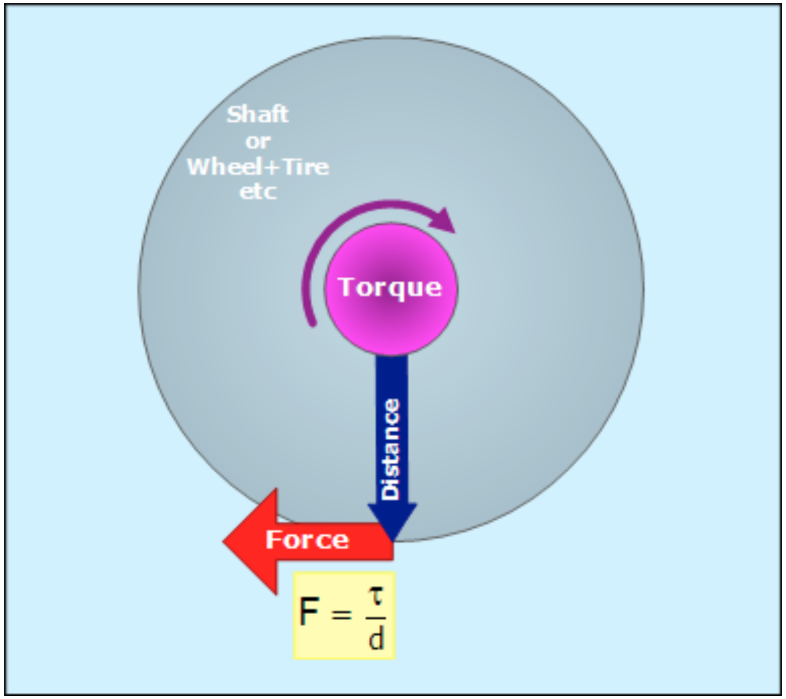
= torque x rotation rate (P = τ x ω)

Torque = "turning force"

Your ability to turn something depends not just on the force you apply but on the lever arm you have

Torque = force x distance   units of energy





Power = energy/time

= torque x rotation rate ($P = \tau \times \omega$)

Transportation: early attempts with steam

Nicolas Cugnot, steam-powered automobile

First car (1769), military tractor for carrying artillery, 2.5 mph

First car accident (1771)

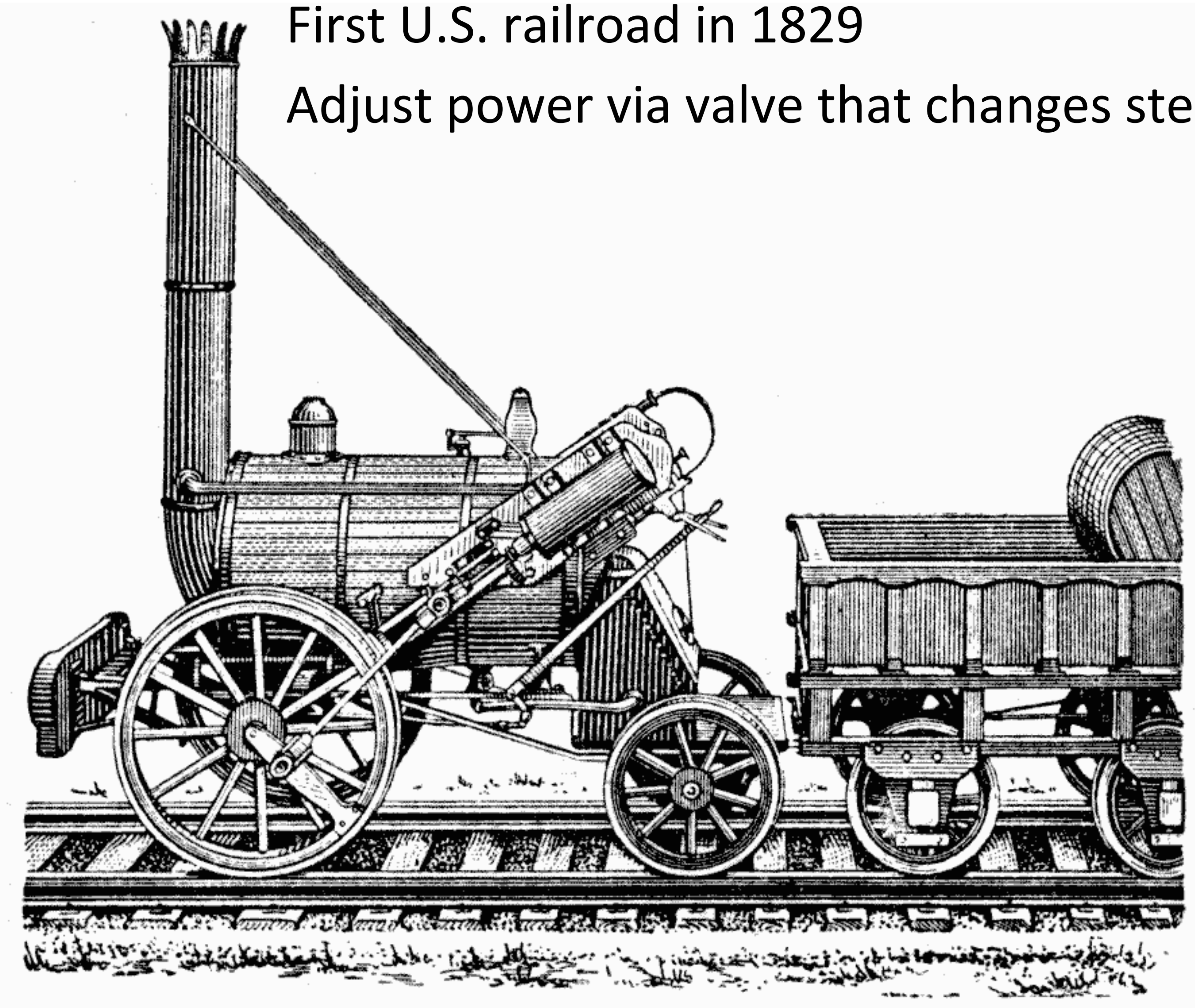
(W. Parsons, U.K: steam car, first fatal accident 1869, driven by his sons)

19th century: steam used mainly for locomotives

First full-scale steam rail locomotive in Britain in 1804

First U.S. railroad in 1829

Adjust power via valve that changes steam intake to piston



Stephenson's Rocket, 1829, winner of Rainhill Trials race between Liverpool and Manchester..

Desire to get away from steam and external combustion

But what fuel to use? What is available?

* Gunpowder
* Coal gas (made by heating and gasifying coal)
* Hydrogen (made chemically)

.. *and only later…*

* Liquid petroleum distillates

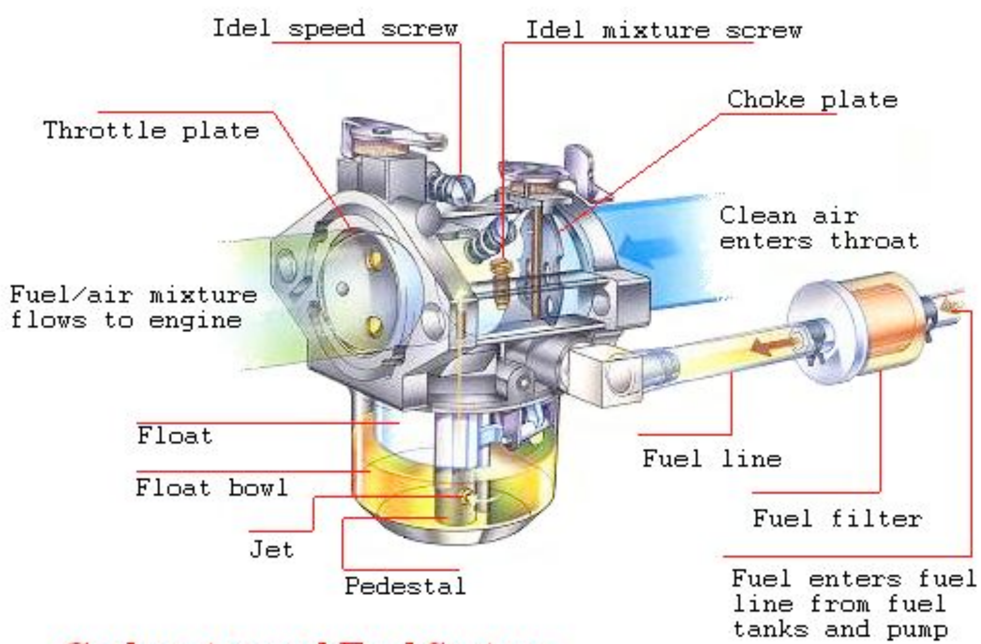
Obstacles to liquid fuel

- Availability

  (little petroleum refining before mid-1800s, even by 1888 petrol purchasable only in drugstores as medicine)

- Mixing liquid fuel into gaseous air

  (required invention of carburetor, later fuel injection)



Carburetor and Fuel System

Internal combustion engine history: early history

1680: Christian Huygens (Holland) designs *(but doesn't build)* an internal combustion engine driven by gunpowder

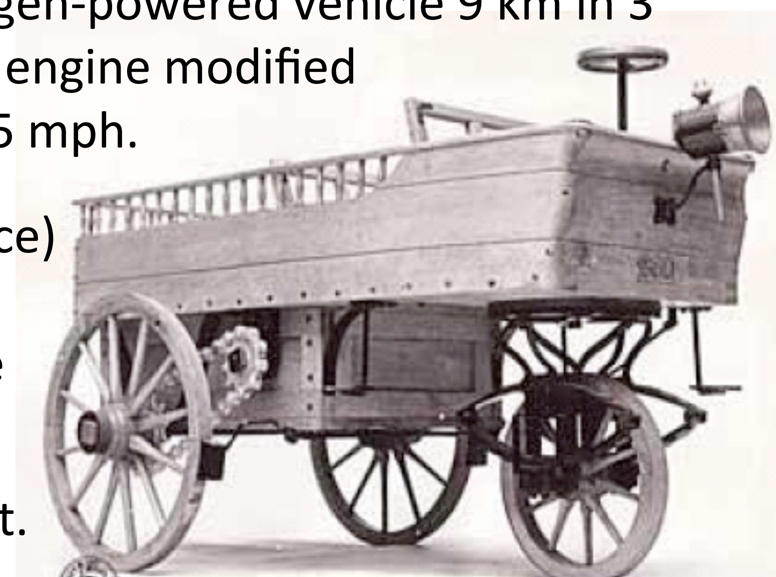
1690: Denis Papin (France) designs *(but doesn't build)* an internal combustion engine driven by gunpowder. Gives up and invents steam engine instead *(against design but no build, later built by Newcomen).*

Early-mid 1800's: experiments with modifying steam engines to run on coal gas (i.e. natural gas).

1858: Jean Joseph Étienne Lenoir (France) patents spark-ignition 2-stroke ICE running on coal gas. In 1863 drives hydrogen-powered vehicle 9 km in 3 hours (1.8 mph). Also drives vehicle with engine modified to run on liquid petroleum : 7 miles at 4.5 mph.

1862: Alphonse Eugène Beau de Rochas (France) designs and patents *(but doesn't build)* a four-stroke engine with compression cycle

1872: George Brayton (U.S.) develops 2-stroke gas/kerosene engine, ct. pressure combust.



Hippomobile, ~400 sold

The birthplace of the internal combustion engine was not France

Internal combustion engine

President Obama, State of the Union speech, Feb. 2009, on bailing out Detroit automakers:

"The nation that invented the automobile cannot walk away from it."

Internal combustion engine

Edmunds *Inside Line, 2009*:

"In what will surely be seen as a provocative move by the new administration, President Barack Obama announced last night in a televised address to the U.S. Congress that all inventions of note from at least the last 200 years will now be credited to Americans.

The president revealed last evening that credit for the invention of the automobile will be transferred from one Karl Benz of Germany to an unspecified American."

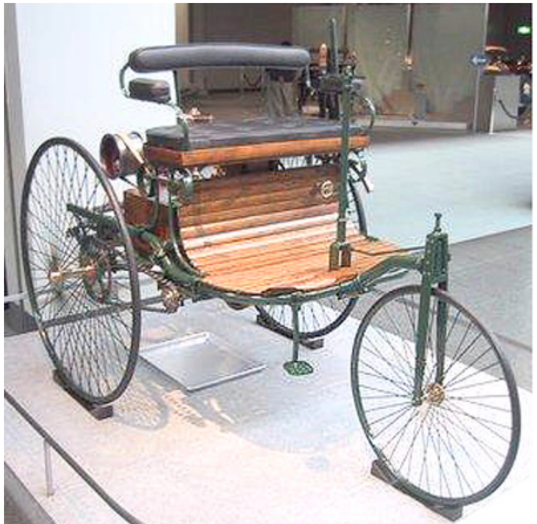
Internal combustion engine history:
development in German-speaking countries

1876: Nicolaus Otto builds workable, commercial version of 4-stroke gas *(not gasoline!)* engine, patents it (again). Now known as "Otto cycle".

1879: Karl Benz gets patent on 2-stroke version of gas-fueled Otto engine.

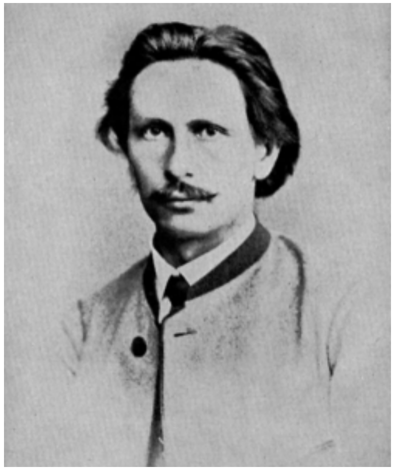
1885: Karl Benz builds 3-wheeled automobile with 4-stroke engine, 2/3 hp
patent 1886. also patents: spark ignition, sparkplug, carburetor, clutch, gear shift, radiator

Benz Patent Motorwagen 1885 – gas or petrol use



Bertha Benz. 1888 first test drive, 65 miles Mannheim-Pforzheim and back

Karl Benz



Internal combustion engine history:

Bertha Benz's bold drive

`Bertha was a wife, but also an investor, and a shrewd marketer. She understood that in order for this to be a success, people had to actually *see* the cars run and drive, and she knew her husband would never attempt anything more than the short test runs he'd been driving. Bertha knew something more dramatic was needed.

And so, one of history's greatest "f--- it, I'm doing this" moments was born.

Bertha took the three-wheeler to see her mom. This doesn't sound like a big deal now, but then it was like saying "I'm gonna go visit my mom who lives on an orbiting platform, and to get there I'm going to take this experimental anti-gravity pod that runs on niobium, which I'll just figure out how to find along the way. See ya!" '

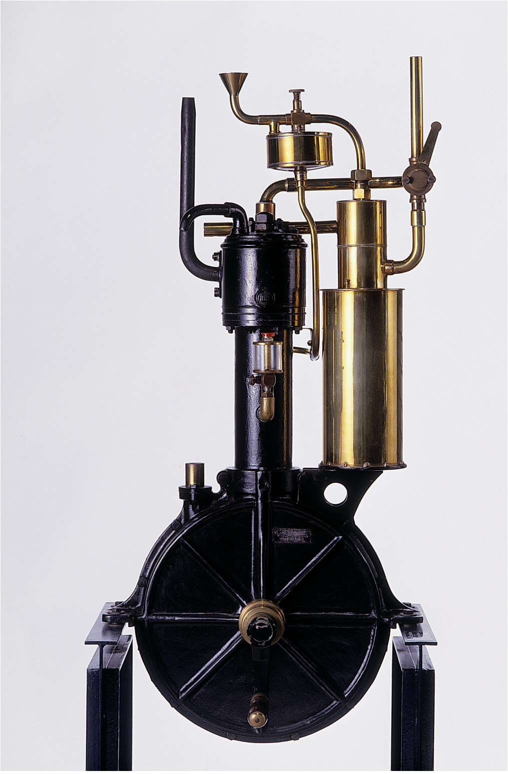
----- *Jason Torchinsky, Jalopnik*

Image: Bertha Benz on the Patent Motorwagen, date unknown. On the actual ride she took her 14- and 15-year old sons. Image from Ca. Automotive Museum.

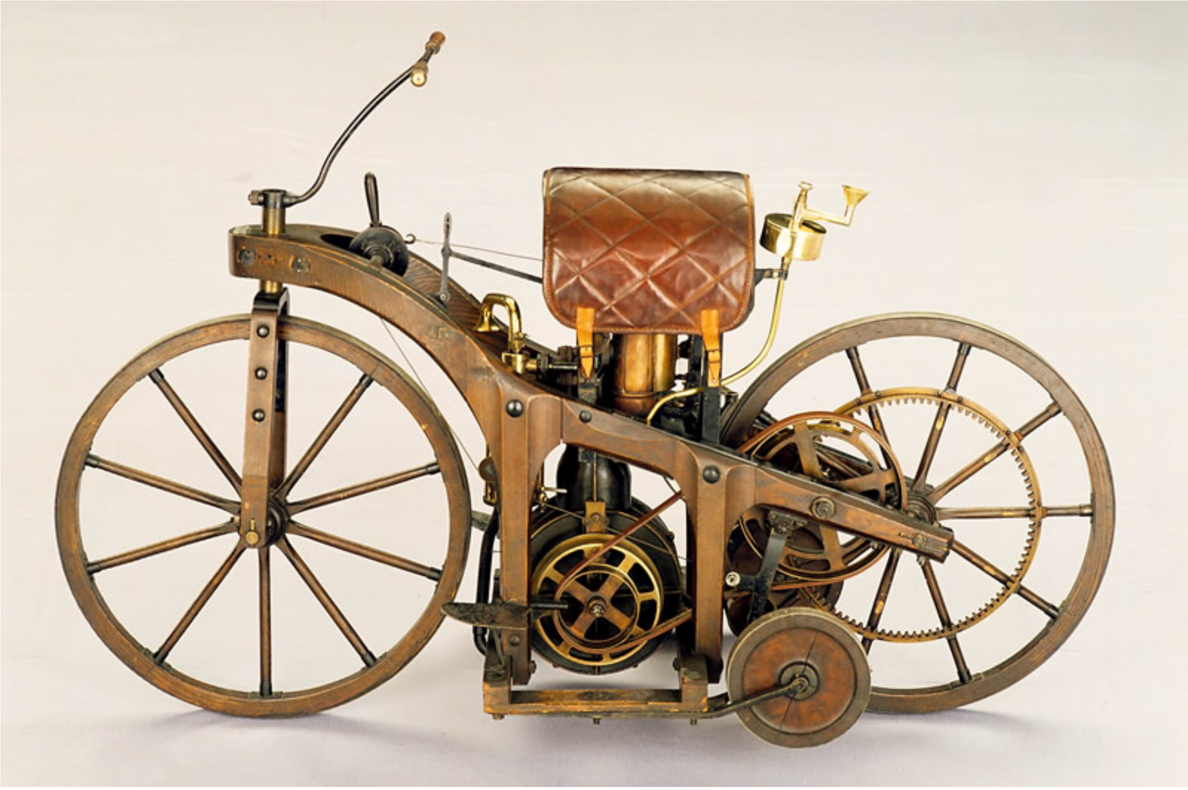
Internal combustion engine history:
multiple developments in German-speaking countries

1885: Daimler & Maybach (having quit Otto's company) develop advanced 4-stroke engine, attach it to motorcycle

Daimler-Maybach grandfather-clock engine
(1885, horizontal cylinder. Image: Daimler.com)



Daimler-Maybach motorcycle, 1885
(replica. Image: Daimler.com)

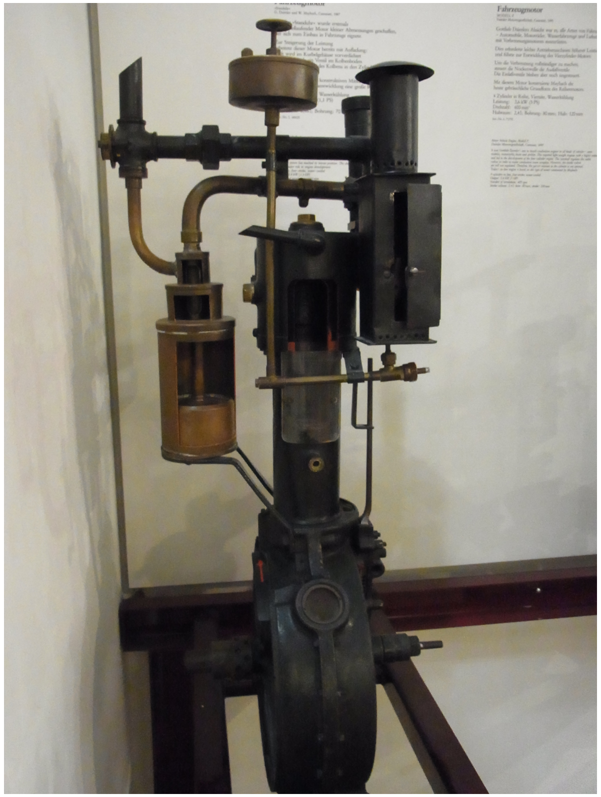


Internal combustion engine history:
multiple developments in German-speaking countries

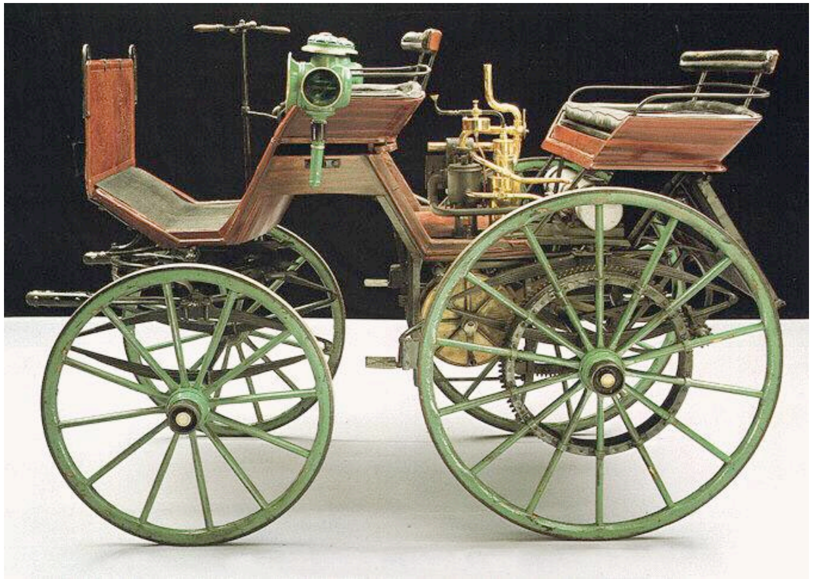
1885: Daimler & Maybach develop advanced 4-stroke engine, attach it to motorcycle

1886-1889: Daimler & Maybach makes 4-wheeled automobile
4-cylinder engine, 10 mph top spd, first sale in 1892

Daimler-Maybach engine, 1887
(at Deutsches Museum)



Daimler-Maybach automobile, 1886 (VintageWeb)



Internal combustion engine history:

multiple developments in German-speaking countries

1891: Benz forms Benz & Cie co.

1899: 430 workers, 572 cars sold world's largest auto company, but production is not fast

1885: Daimler & Maybach develop advanced 4-stroke engine, attach it to motorcycle

1886-1889: Daimler & Maybach makes 4-wheeled automobile

4-cylinder engine, 10 mph top spd, first sale in 1892

Benz & Cie Vikoria automobile, 1894
(Karl and Bertha onboard, image: Wikipedia)

Daimler-Maybach automobile, 1886 (VintageWeb)

Merger to Daimler-Benz 1926

Internal combustion engine history:
--> production improvements in U.S.

1893: First auto manufacturing in U.S. (Duryea Co., MA), flowering of many small companies

1896: Henry Ford starts company, Detroit

1908: Mass production of Ford Model Ts

Ford Model T assembly line, 1924.

Ford Model T, 1908. (repainted, howstuffworks.com)

Two-stroke engine

Simple, cheap

First stroke:

Piston rises, compresses fuel/air mix

Meanwhile, unburnt fuel is drawn into crankcase

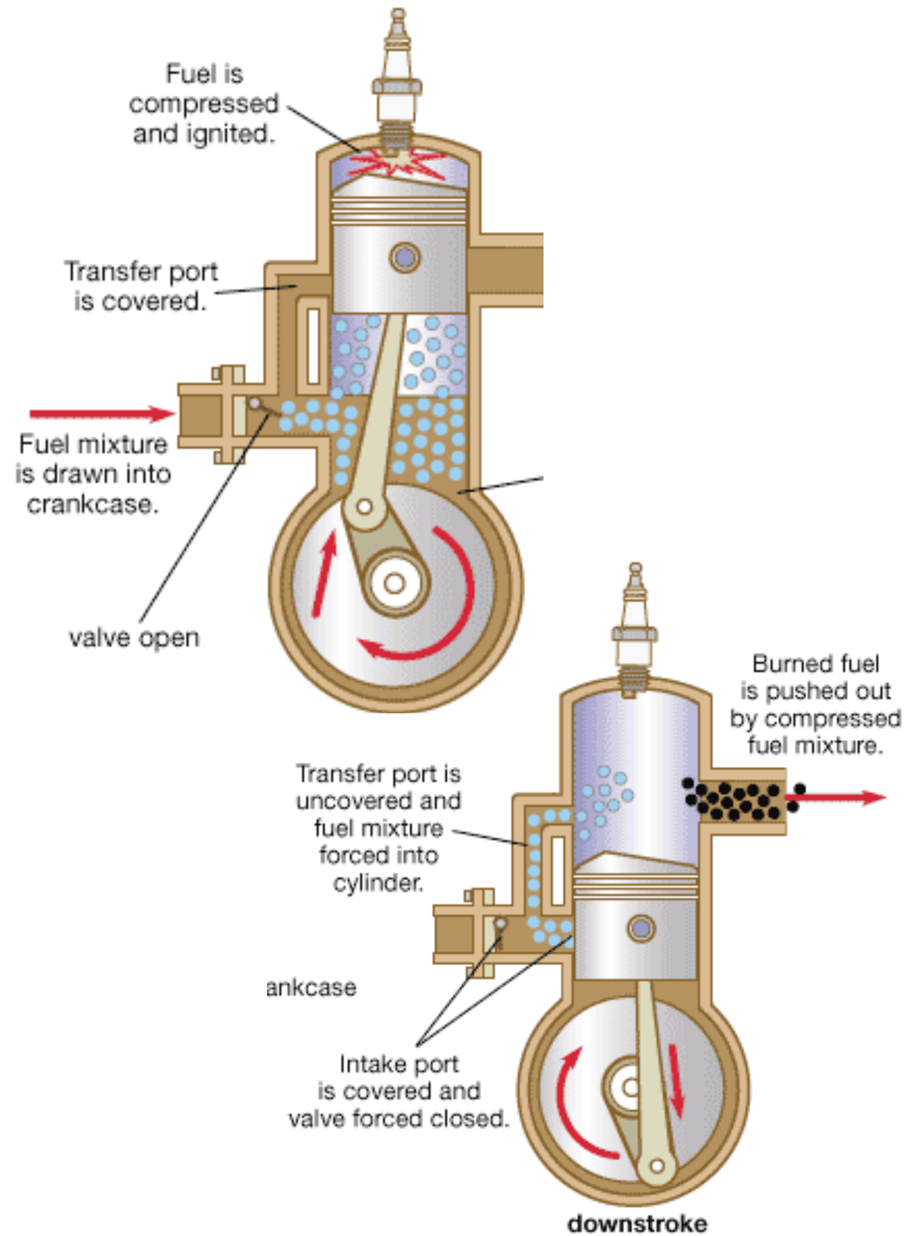
Second stroke:

Fuel/air is ignited

Piston driven down

Exhaust gas leaves cylinder

Fuel/air mixture enters cylinder

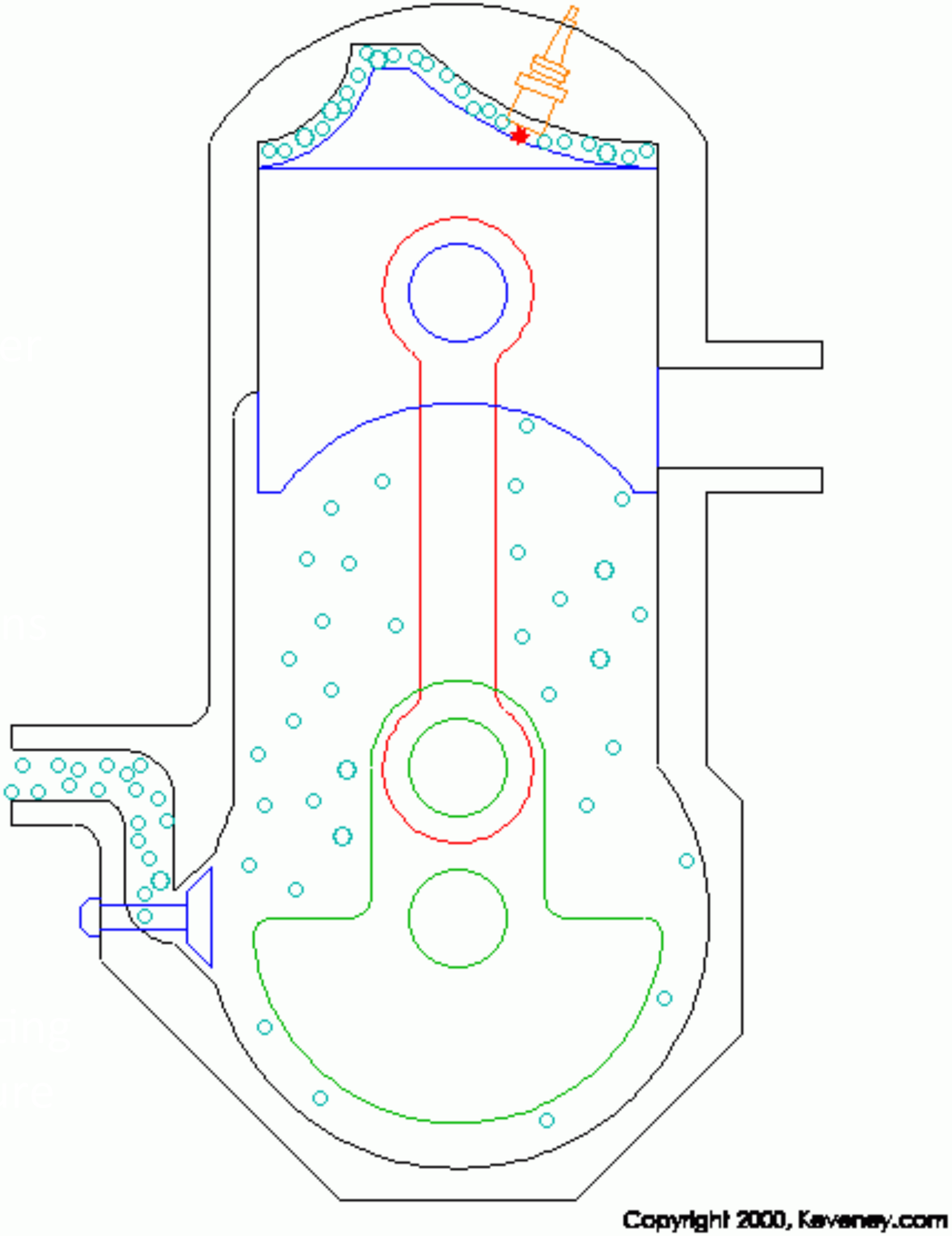


Two-stroke engine

Simple, cheap

Advantages:

Disadvantages:



Two-stroke engine

Simple, cheap

Advantages:

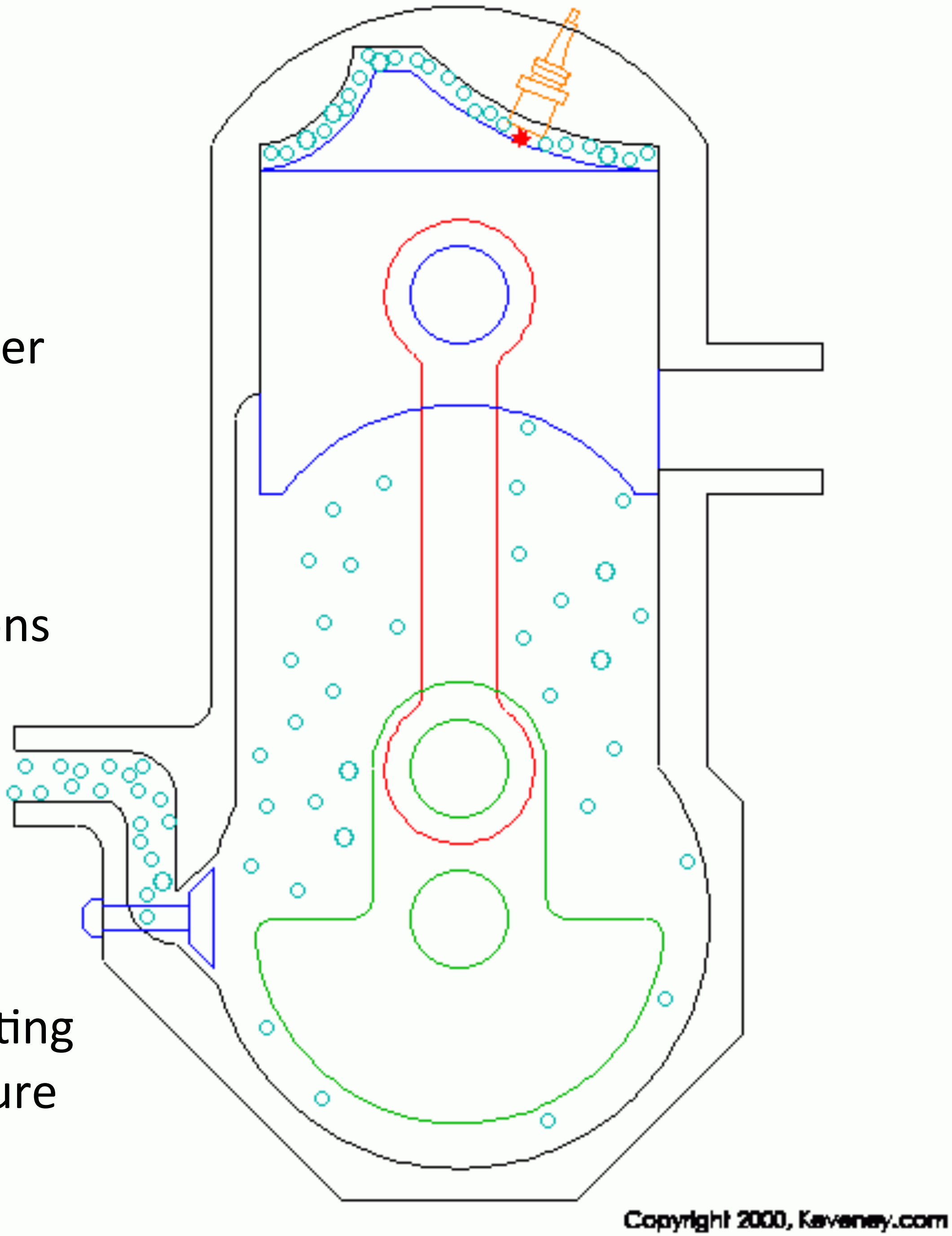
Higher power-to-mass since is never "off" – each stroke is power stroke. Smoother power in one-cylinder engine

Therefore: engine of choice for cheap or hand-carried applications

Disadvantages:

Some unburned fuel escapes – very polluting

Since fuel fills crankcase, lubricating oil must be mixed into fuel mixture – *even more polluting*

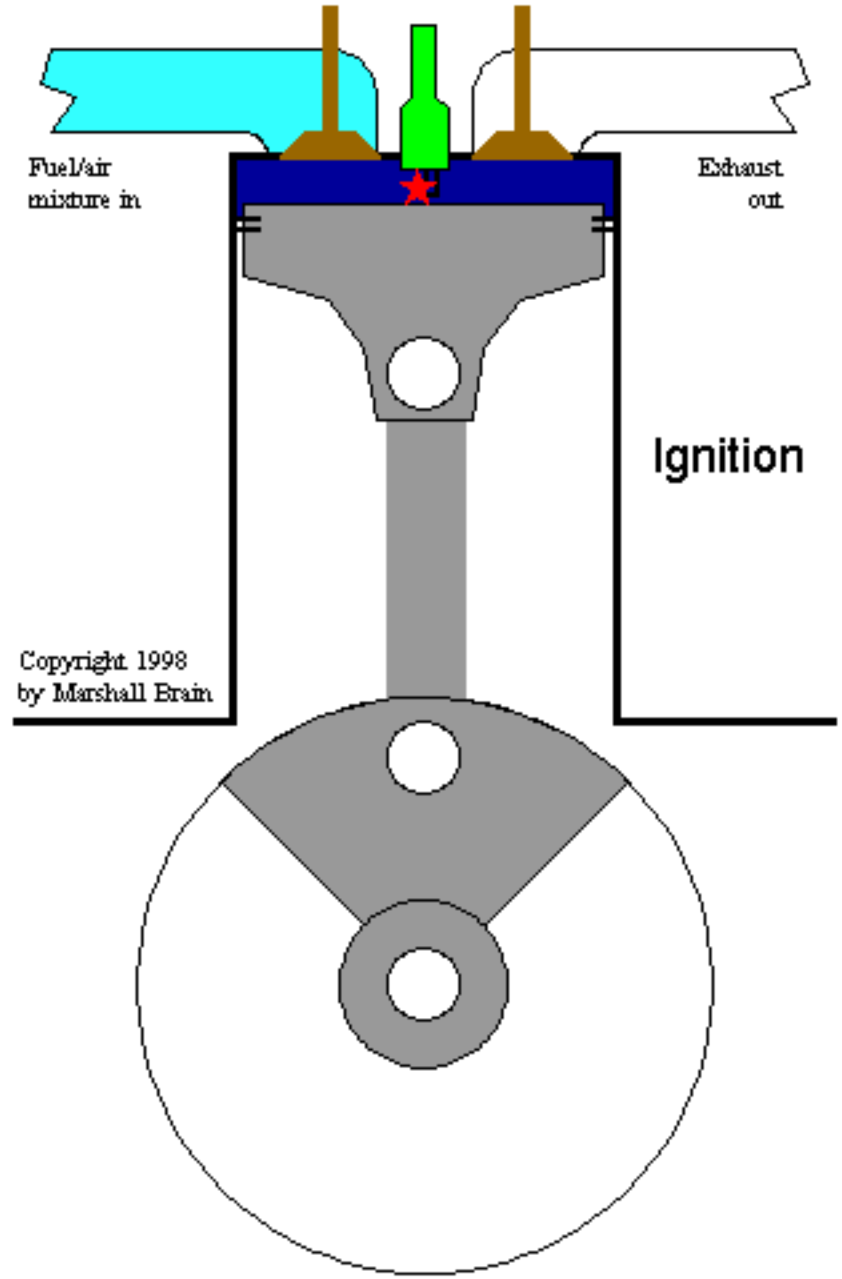


Four-stroke engine: Otto cycle
driver of most transportation

One preparation cycle and one power cycle *(down/up/down/up)*

1. Intake
2. Compression
3. Combustion
4. Expansion *(Exhaust)*

Note use of spark plug to set off combustion (same for 2-stroke)



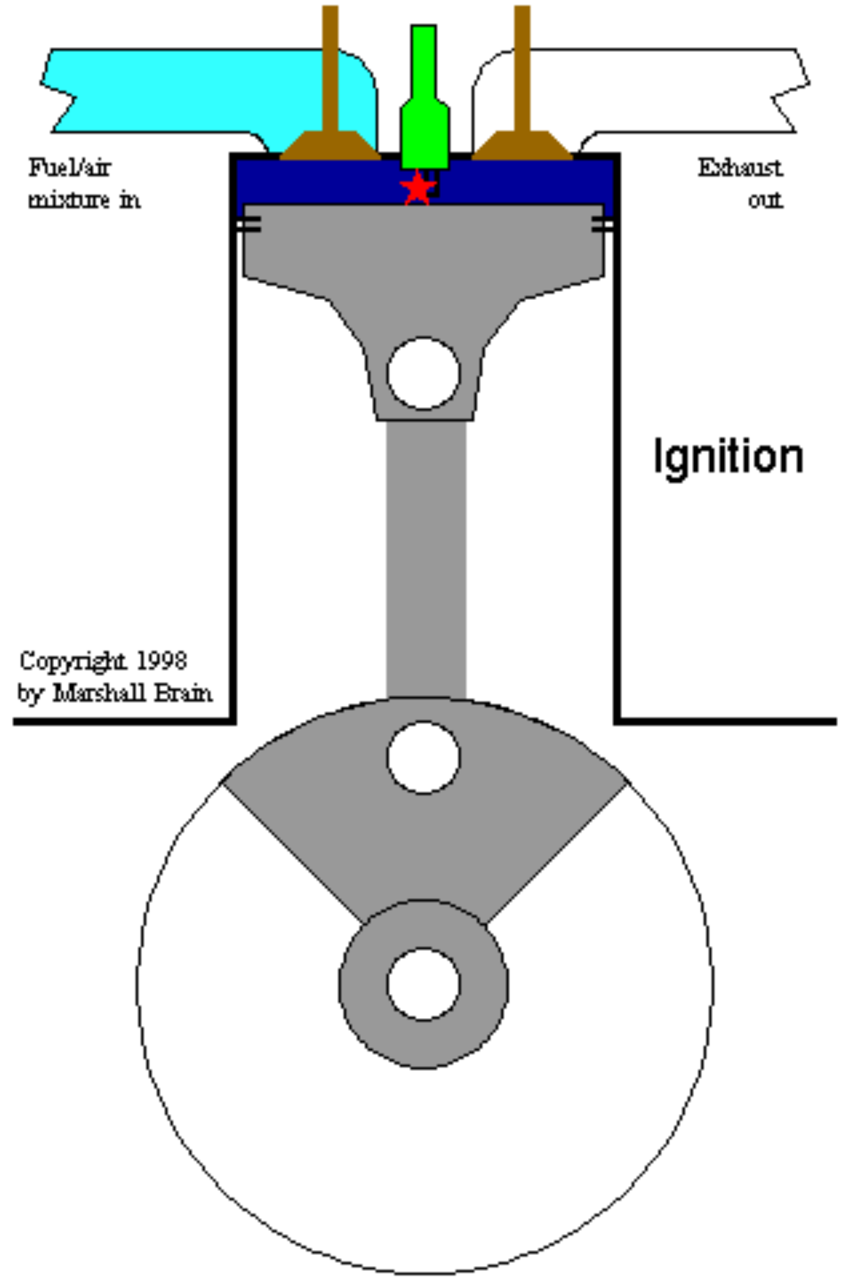
Four-stroke engine: Otto cycle
driver of most transportation

Advantages:
Produces heated, compressed, very dense fuel/air mixture

Separation of unburnt fuel/air from combustion cycle

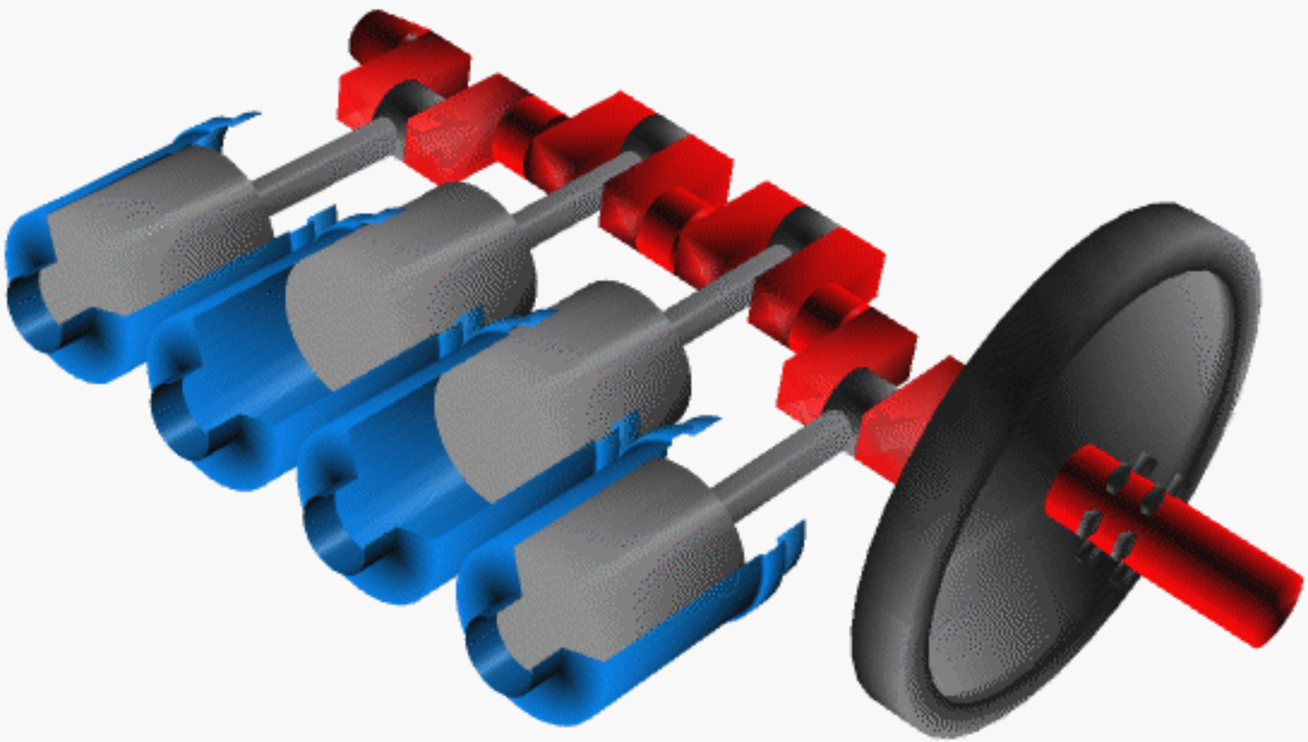
Disadvantages:
"off" half the time – half the power-to-mass ratio that it might have

Generally have at least two cylinders, so that when one is "off" the other can provide the push to keep rotating the shaft



Four-stroke engines: generally have pairs of cylinders

Gasoline engines for automobiles typically have 4-8 cylinders
Out-of-phase cylinders provide force to drive pistons through compression phase and yield balanced power



Note central crankshaft turns linear piston motion into rotational motion and puts work into the same shaft

More power = more cylinder volume

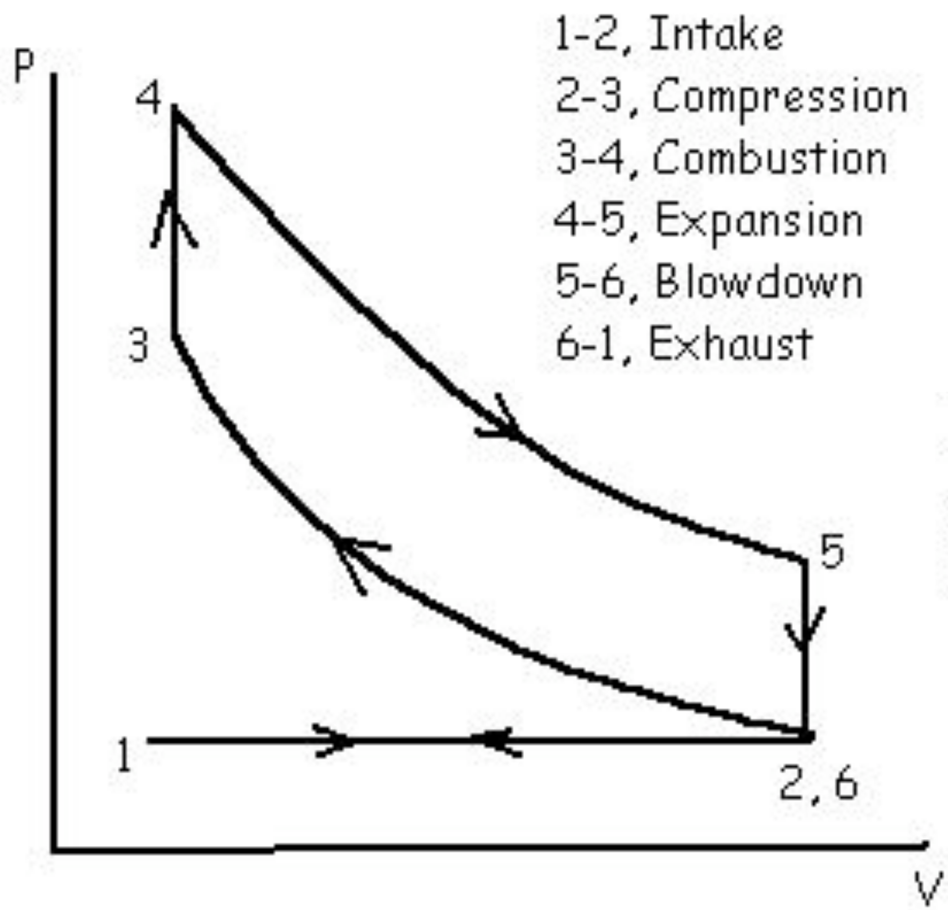
get more volume from bigger cylinders, or more cylinders

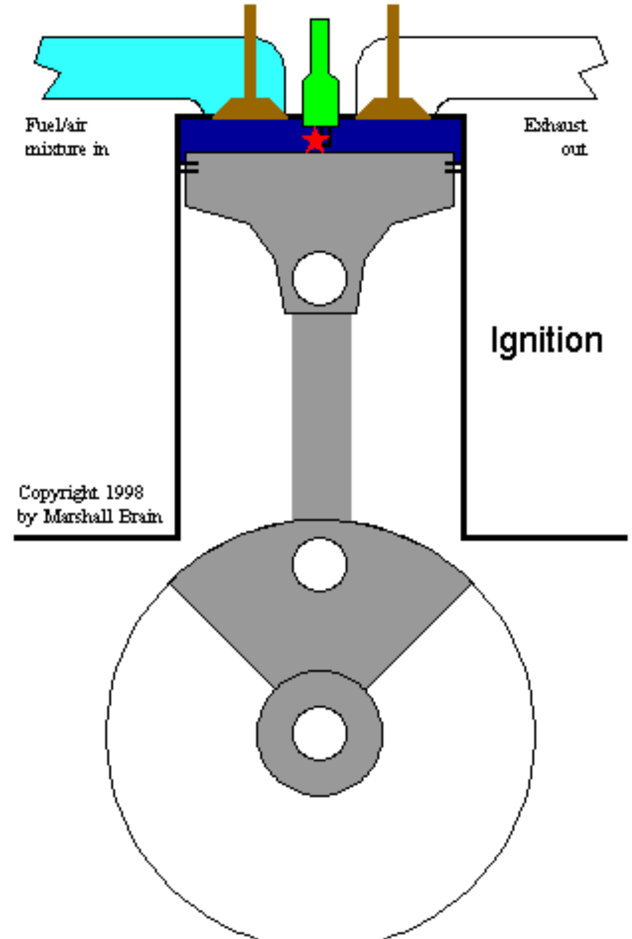
Some high-power automobile engines have 8 cylinders, hence “V8”

BMW M3 V8 Engine: 4.0-litres total, i.e. 4000 cc in 8 cylinders
(lab lawnmower engine ~ 100 cc (1 cylinder)

Thermodynamic cycles: Otto cycle

Fast combustion at constant volume. Sparkplug to ignite quickly and completely.



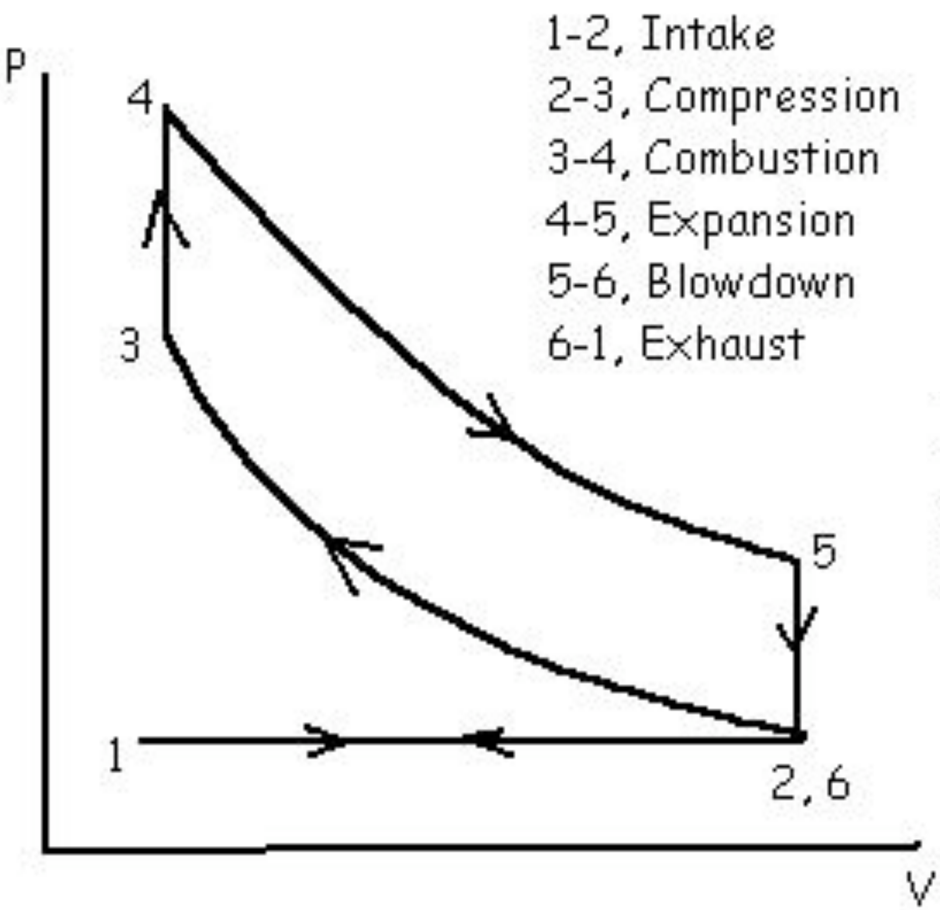


ideal Otto efficiency = $1 - (1/r)^{\gamma-1}$ where r = compression ratio V_1/V_2

(γ = specific heat ratio, property of the gas, ~ 1.4 for air)

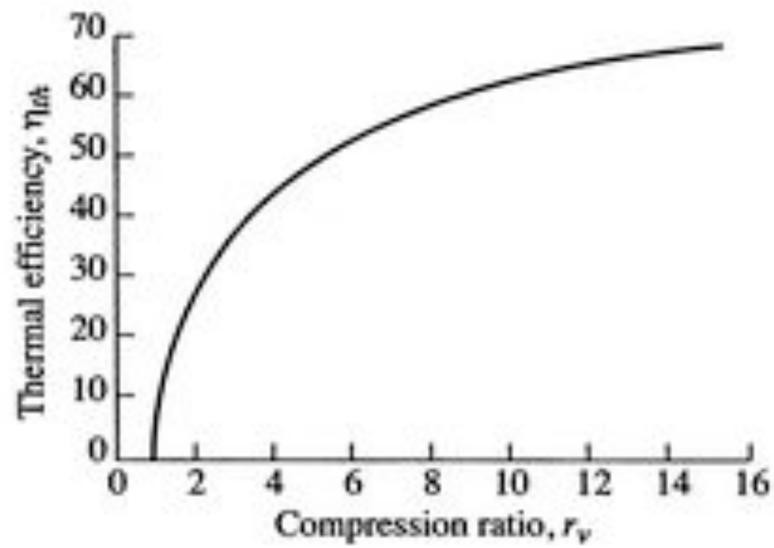
Thermodynamic cycles: Otto cycle

Fast combustion at constant volume. Sparkplug to ignite quickly and completely.



Efficiency is a function of compression ratio, so design for high ratios: r ~ 10 in cars

Figure: web.mit.edu



ideal Otto efficiency = $1 - (1/r)^{\gamma-1}$ where r = compression ratio V_1/V_2

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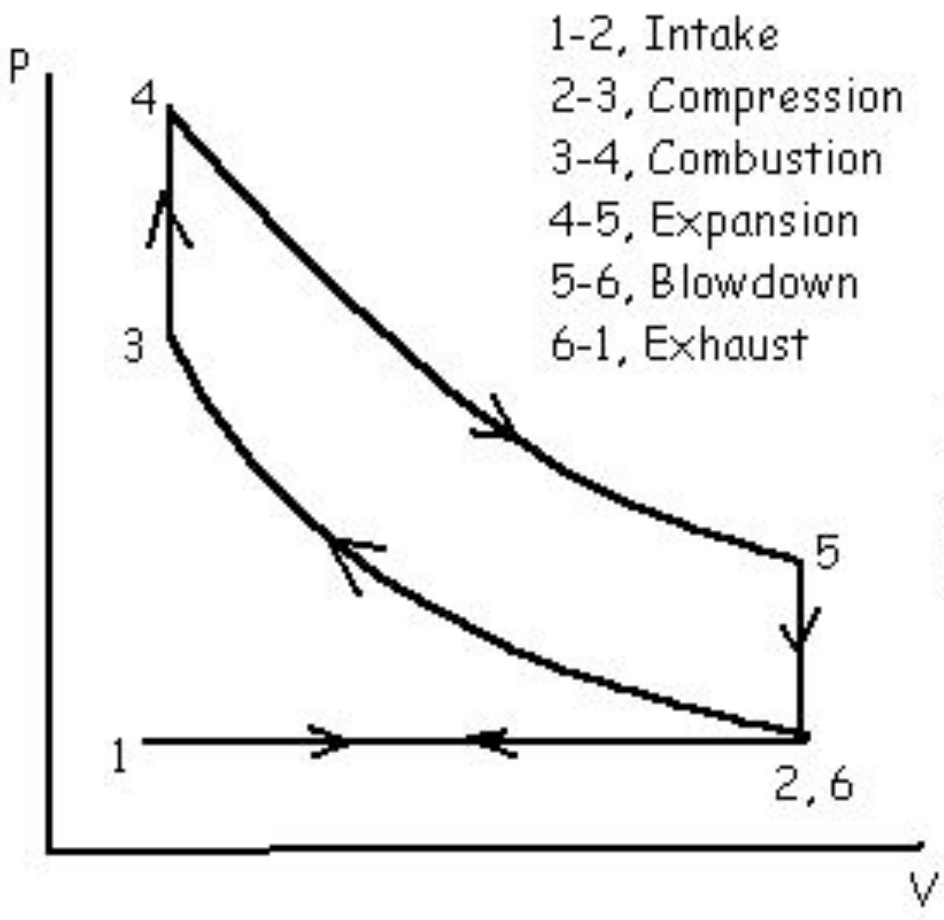
Thermodynamic cycles: Otto cycle

But do you need to combust at constant volume? Wastes power (area on graph)
You would get more power if you continued compressing gas before igniting...



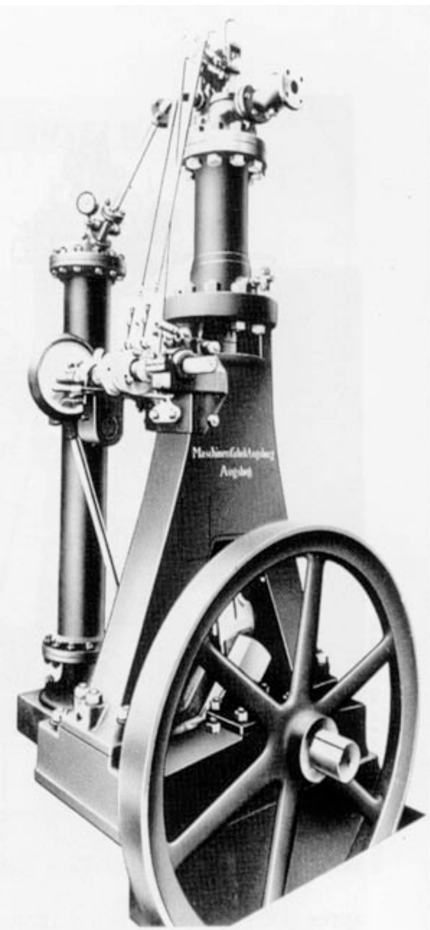
Engine history: *non-Otto-cycle engines*

2 other famous German-speaking auto inventors: who were they?

Both exhibited at the 1900 Paris Exposition

One *(former electric shop worker)* won the speed competition with an **all-electric car** carrying a 900-pound battery with a 38 mile range & top speed of 36 mph.

The other *(former steam engine designer)* won the Grand Prix of the whole Exposition for a new **bio-fueled engine** running on peanut oil, operating on a new thermodynamic cycle he'd invented from 1st principles

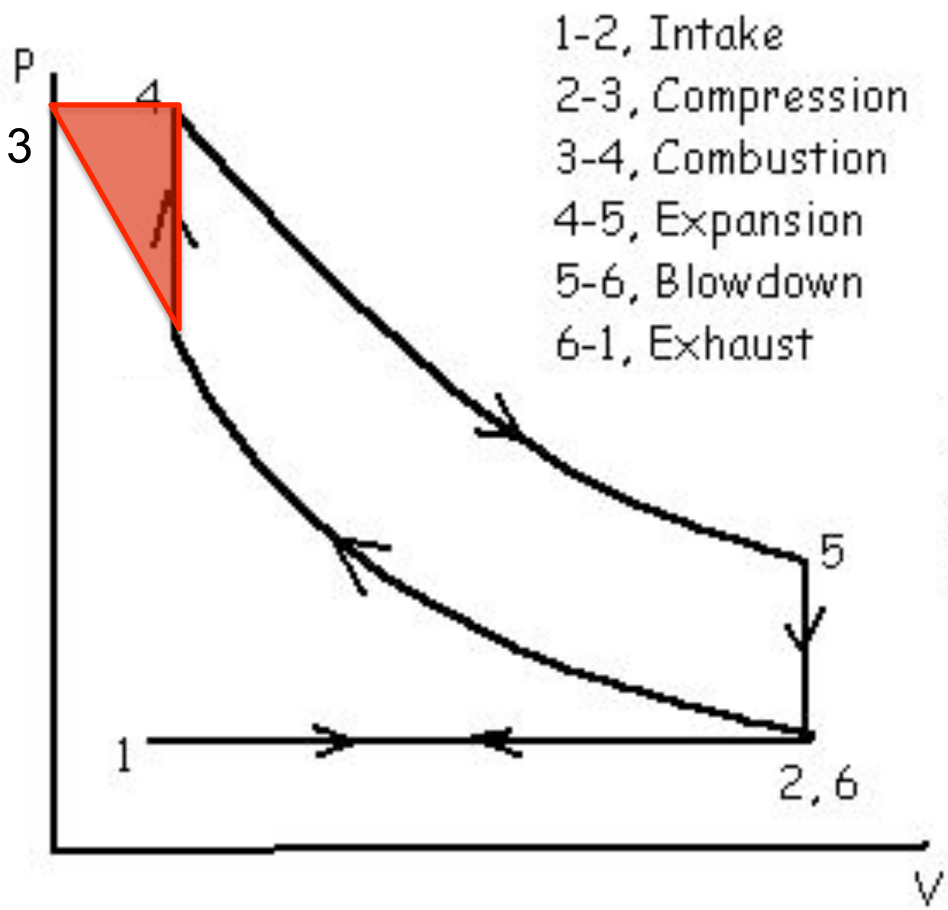


Diesel engine, invented 1893, 17% efficient. Designer: Rudolf Diesel, German-trained

Lohner-Porsche Elektromobil, designer: Ferdinand Porsche, Austrian, age 24. Note electric motors in front wheels.

Thermodynamic cycles: Diesel cycle

But do you need to combust at constant volume? Wastes power (area on graph)
You would get more power if you continued compressing gas before igniting...



Diesel cycle involves
- higher pressure
- lower final volume

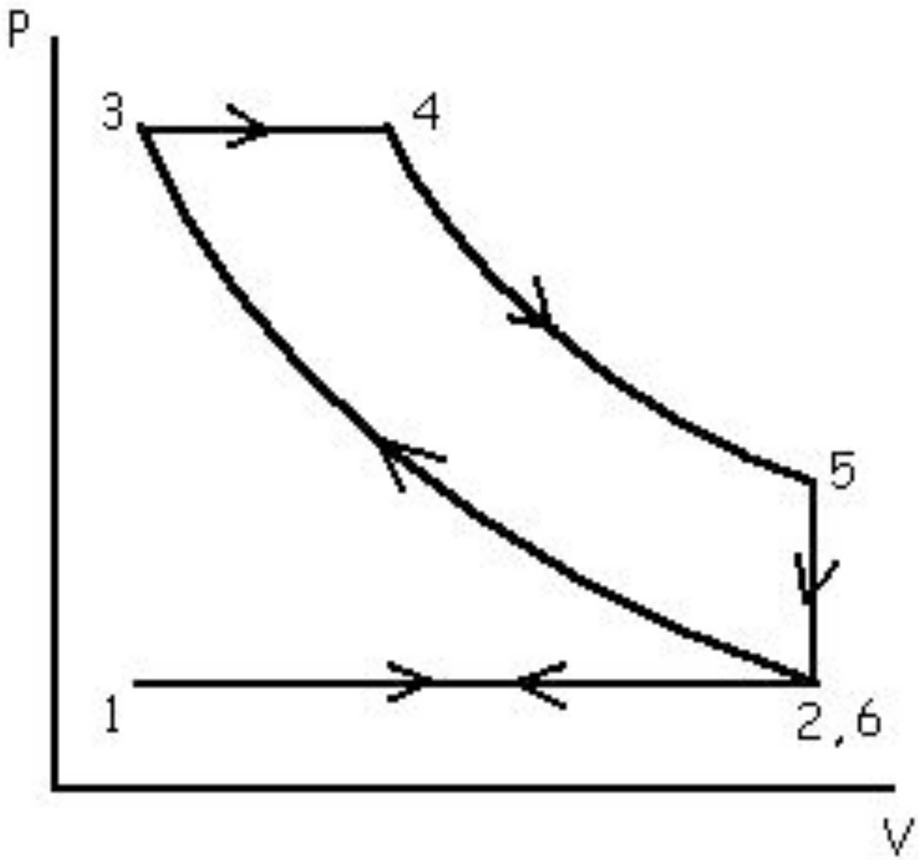
→ higher compression ratio
r ~ 14 – 22 or more

ideal Diesel efficiency = 1 – [$(1/r)^{\gamma-}$ * $(\alpha^{\gamma} -1)/(\gamma(\alpha -1))$]

where α is the "cutoff ratio" V_4/V_3. Lower than Otto for a given r, but r is bigger for Diesel.

Thermodynamic cycles: Diesel cycle

Cycle designed for higher efficiencies.



Diesel cycle achievable ***only*** if system can withstand higher pressures before igniting.

1) First compress air, THEN spray fuel in to control ignition.

2) Use specially designed "Diesel fuel" that can reach higher pressures before ignition (originally used peanut oil)

Diesel fuel is less volatile than gasoline, ignites on compression... but only at very high P

ideal Diesel efficiency = $1 - [(1/r)^{\gamma-} * (\alpha^{\gamma} - 1)/(\gamma(\alpha - 1))]$

where α is the "cutoff ratio" V_4/V_3. Lower than Otto for a given r, but r is bigger for Diesel.

Diesel: advantages

1. **Higher compression ratios = higher temperatures = higher efficiency** (in practice 40%, up to 55% in some demonstrated engines)

   → *Fuel efficiency greater than with gasoline hybrids*

2. **Reliability:** no sparkplugs – ignition occurs from compressional heating alone

3. **More torque at low speeds** - very useful for pushing big loads at slow speed.

4. **Lubrication:** fuel is better lubricant than gasoline, so piston rings and cylinder bores last longer

Diesel: disadvantages

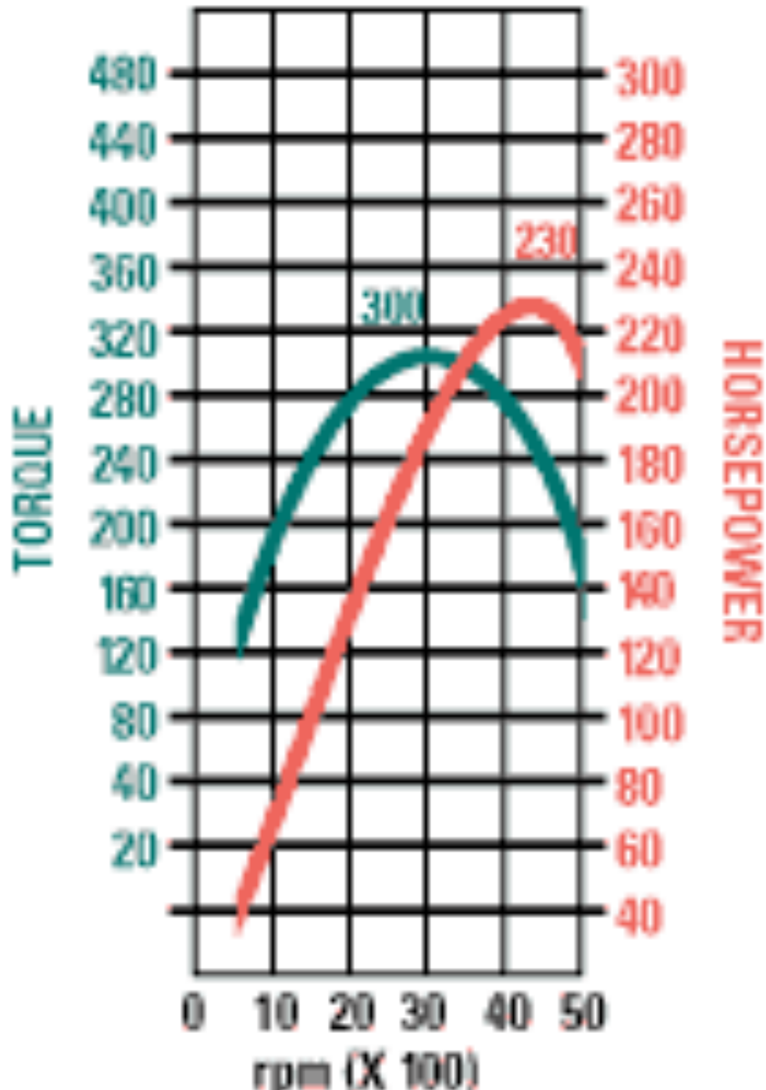
1. **Weight –** heavier engine construction to deal with higher pressures

2. **Poor torque at high speeds** – bad acceleration when at cruising speed

3. **Inherently polluting -** incomplete combustion gives sooty particulates
   Why? Fuel not pre-mixed outside cylinder but injected just before combustion, after compression.

   Pollution problem greatly fixed in recent engines

NO internal combustion engines runs well at slow speeds



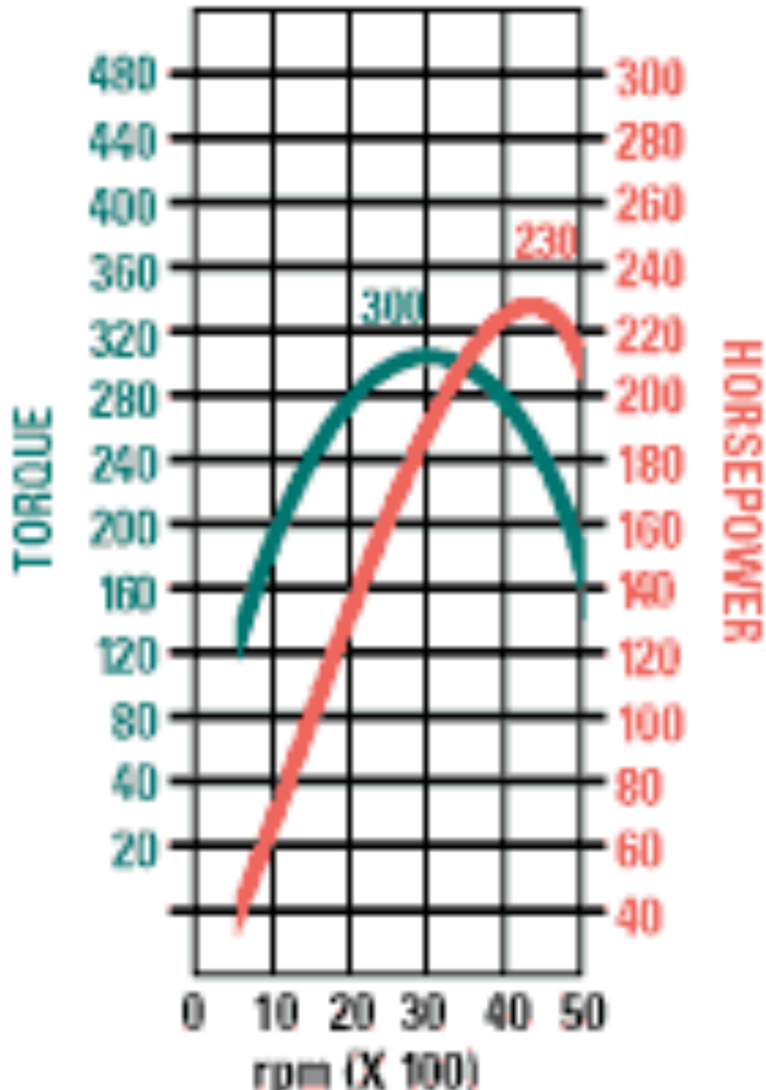
Otto engine, Dodge Ram pickup V8 5.9 L engine, 2004

Fundamental problem with ICEs:

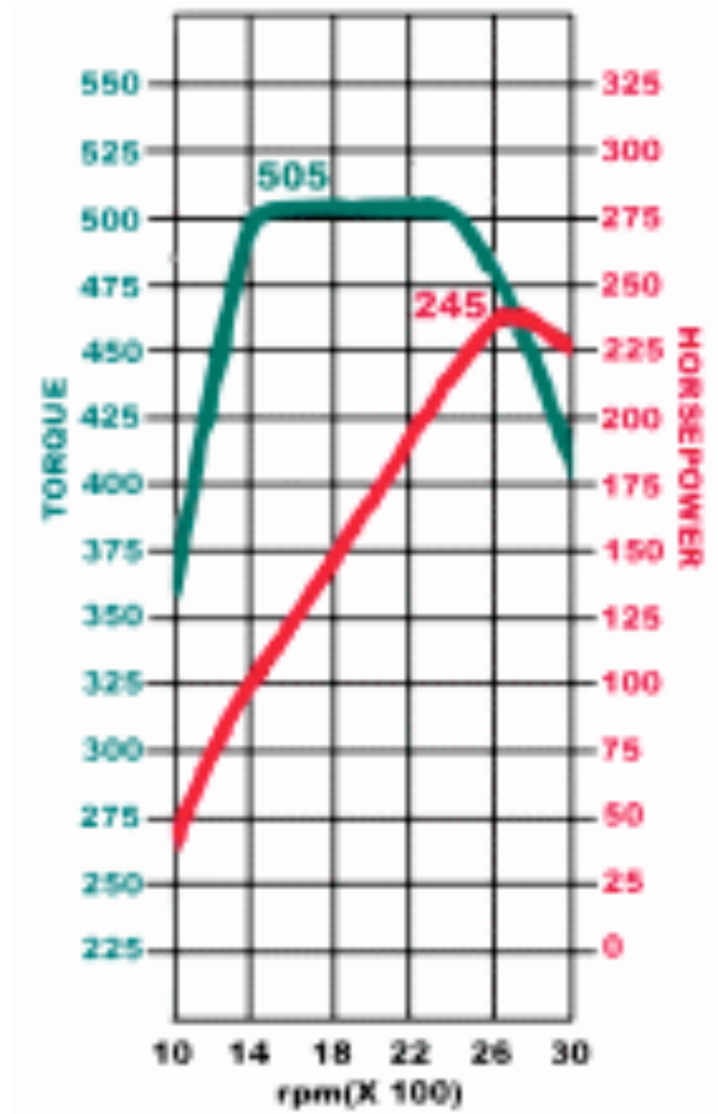
Low torque at low rpm. How do you start the car from a standstill? How do you accelerate?

Note that ICEs do **nothing well at low speed**: not torque, not power, not efficiency (not shown here)

Diesel engine has more torque at low speed than Otto



Otto engine, Dodge Ram pickup V8 5.9 L engine, 2004
peak torque at 3000 rpm

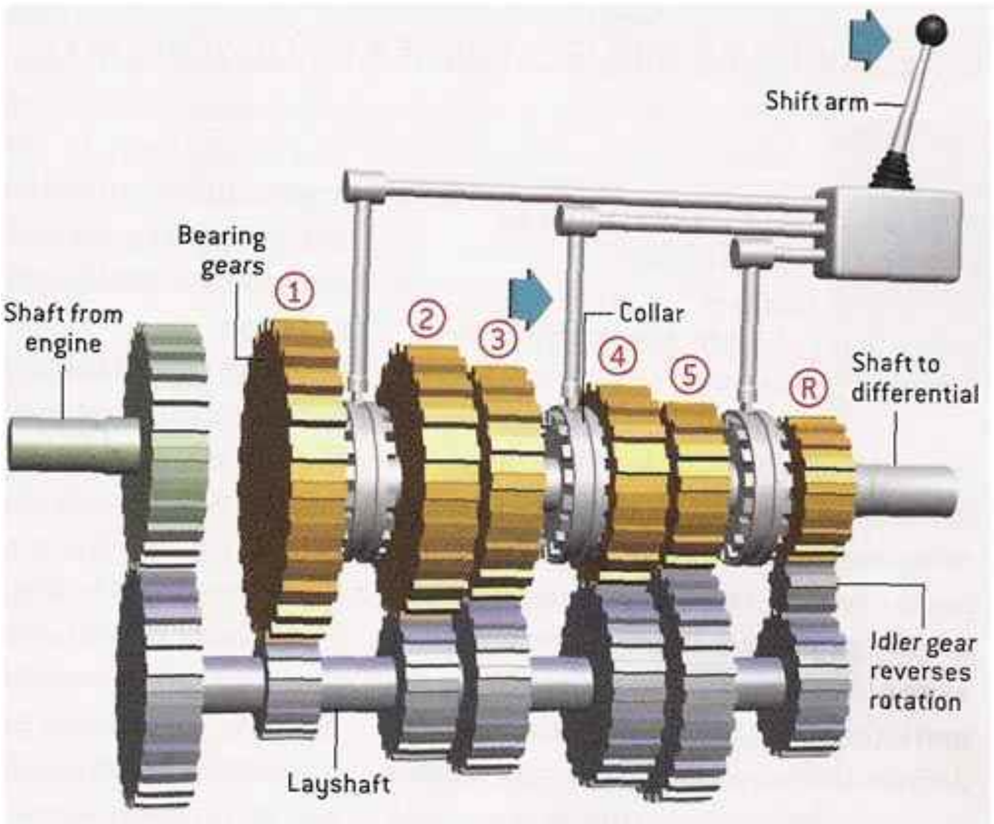


Diesel engine, Dodge Ram pickup 5.9 L, standard output, 2004
peak torque at 1400-2400 rpm

ICEs must run at high speed, else can't make enough torque

Fundamental mismatch between engine and wheel speed

Kludge = **transmission** – a gearing system to allow an ICE to operate at high speed even while vehicle moves slowly



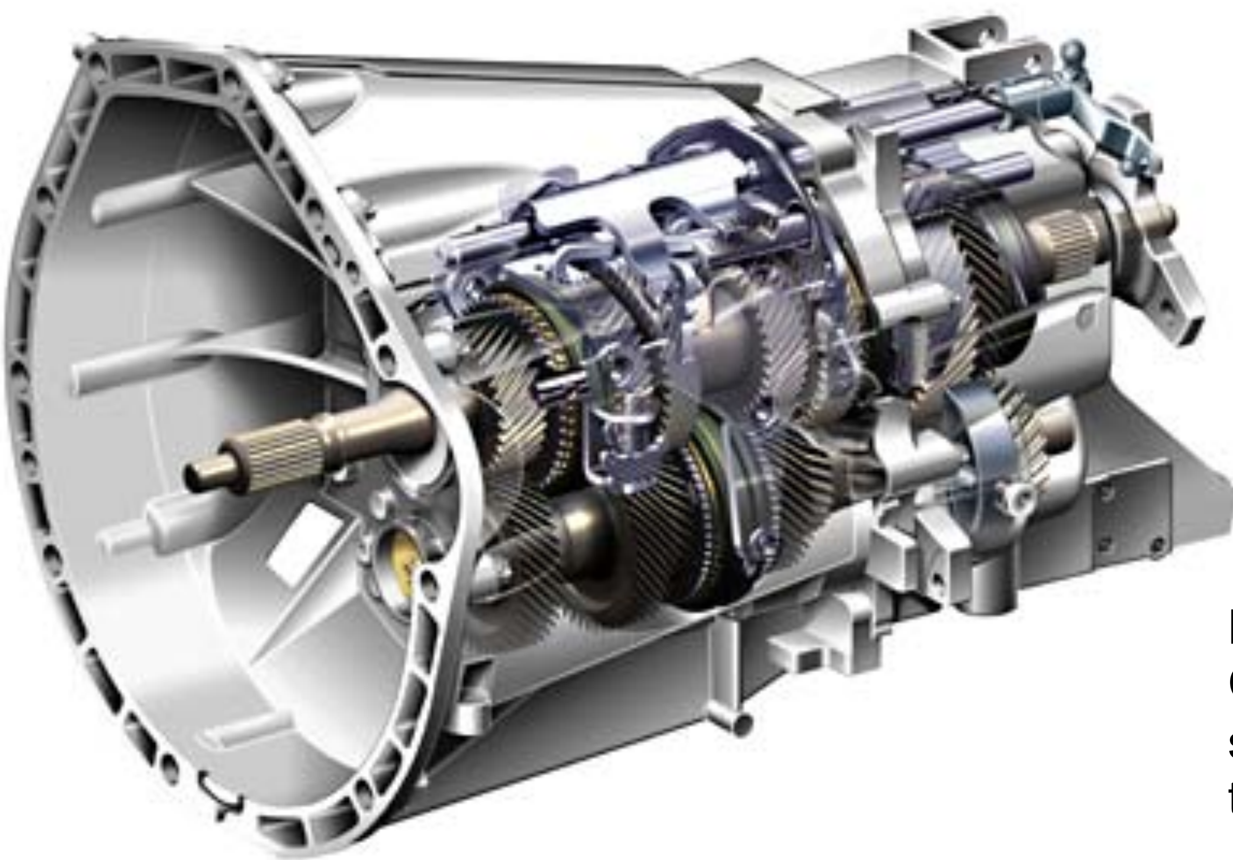
Manual transmission schematic, hyperlogos.org

ICEs must run at high speed, else can't make enough torque

$P = \tau * \omega$. If want power P, and τ is constrained, must have high ω

Fundamental mismatch between engine and wheel speed

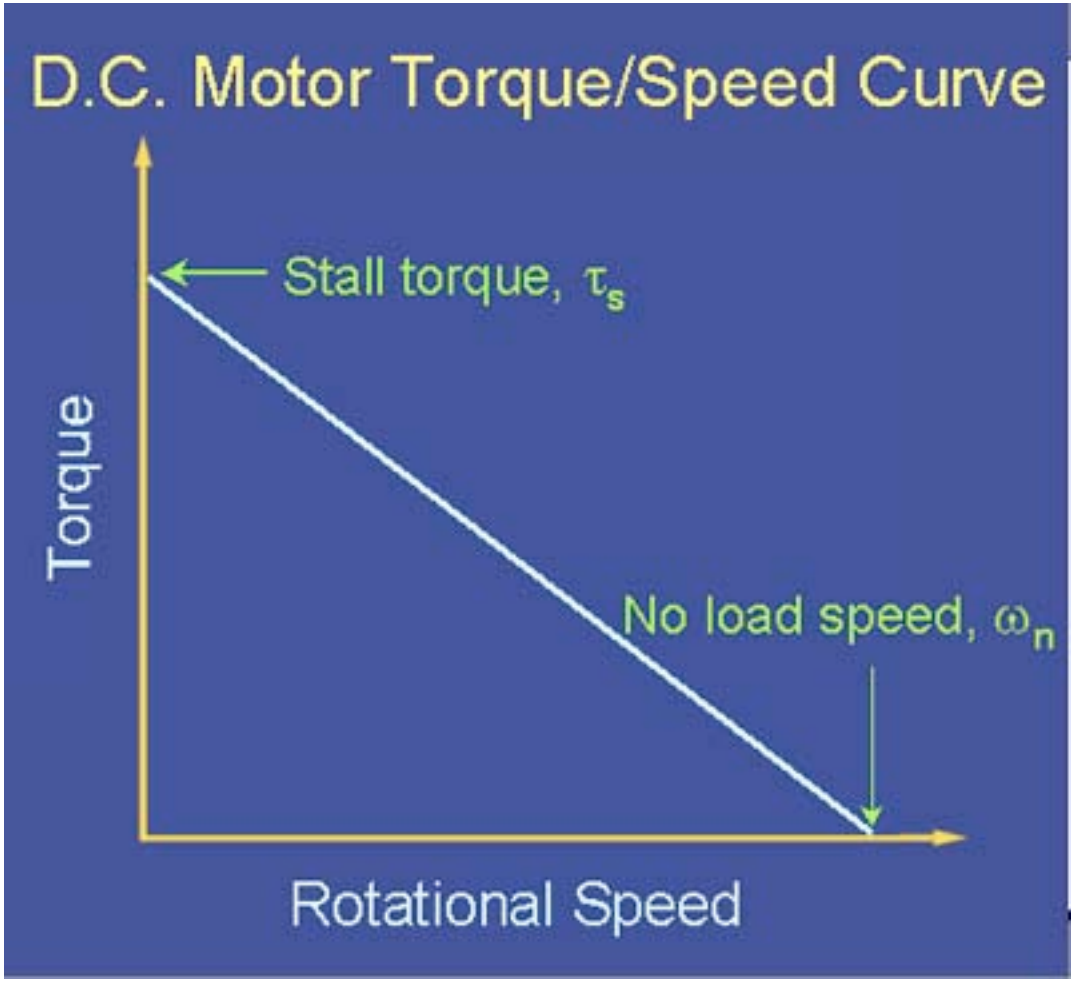
Kludge = **transmission** – a gearing system to allow an ICE to operate at high speed even while vehicle moves slowly



Mercedes-Benz C-class coupe 6-speed manual transmission

DC electric motors avoid this limitation!

DC motor torque is actually *higher* at low speed



Power:
$P = \tau * \omega$

or also
$P = I * V_{back}$
$= a * V_{back} - b * V^2_{back}$

But voltage in DC motor is prop. to ω! So divide both sides by ω...

$\tau \;\; \alpha \;\; (a - b*\omega)$

So max torque when $\omega = 0$. And there's a max speed beyond which engine can't go

Figure: MIT Mech. Eng. 2.007
lancet.mit.edu/motors/motors3.html

Some drawbacks of the ICE

- Engine speed mismatched to wheel speed

  → *requires transmission*

- Single power system

  → *requires drivetrain*

- Single power system but wheels must rotate at different rates (when going around curves)

  → *requires 'differential'*

ENGINE choices **Once you're in ICE world, what do you choose?**

(besides side-effects of pollution, noise, etc, as well as cost/durability/reliability)

1. **Power/mass:** heavier engines harder to move or carry.
   Governs 2- vs. 4-stroke choice.

2. **Efficiency:** how much mechanical work you get out of a given amount of chemical energy.

3. **Torque:** "turning force". Affects how fast you can accelerate, or how big a load you can get moving.
   Tradeoff between 2 and 3 helps govern choice of Diesel vs. Otto vs. electric

(sometimes benefits of electric are too great to pass up...)

What is each engine type best for?

Gasoline: poor torque at low speed, good torque (acceleration) when at cruising spd., light weight

Diesel: higher torque at low speed, less torque at cruise, heavy weight but high power

Electric: max torque at low speed, very little torque once at cruise, heaviest choice: requires generator (or heavy battery)

Locomotives: all diesel-electric trains are series hybrids

Hybrid technology: engine (2-stroke diesel for maximum power) drives generator; electricity carried to each wheel to drive separate electric motors. *No need for battery in between.*

Right: EMD 12-710G3B engine, 3200 hp (2.5 MW)

12 cylinders, each with 11.6 liter displacement, twice that of the biggest gasoline engines. 16:1 compression ratio.

The generator is 6 feet in diameter, weighs ~18,000 pounds, turns at 900 rpm (very slowly).

Figure: Wikipedia

Locomotives: all diesel-electric trains are series hybrids

Individual motors weigh 6000 pounds and draw over 1000 amps.

Electric motors providing braking (avoid friction brakes). Electric motors act as generators and torque slows train.

Electrical energy from braking not necessarily recovered – often dissipated in resistors on top of train.

Batteries to store electrical energy are expensive and trains don't brake often.

Figure: howstuffworks.com

Electric motors driving wheels have single fixed gear

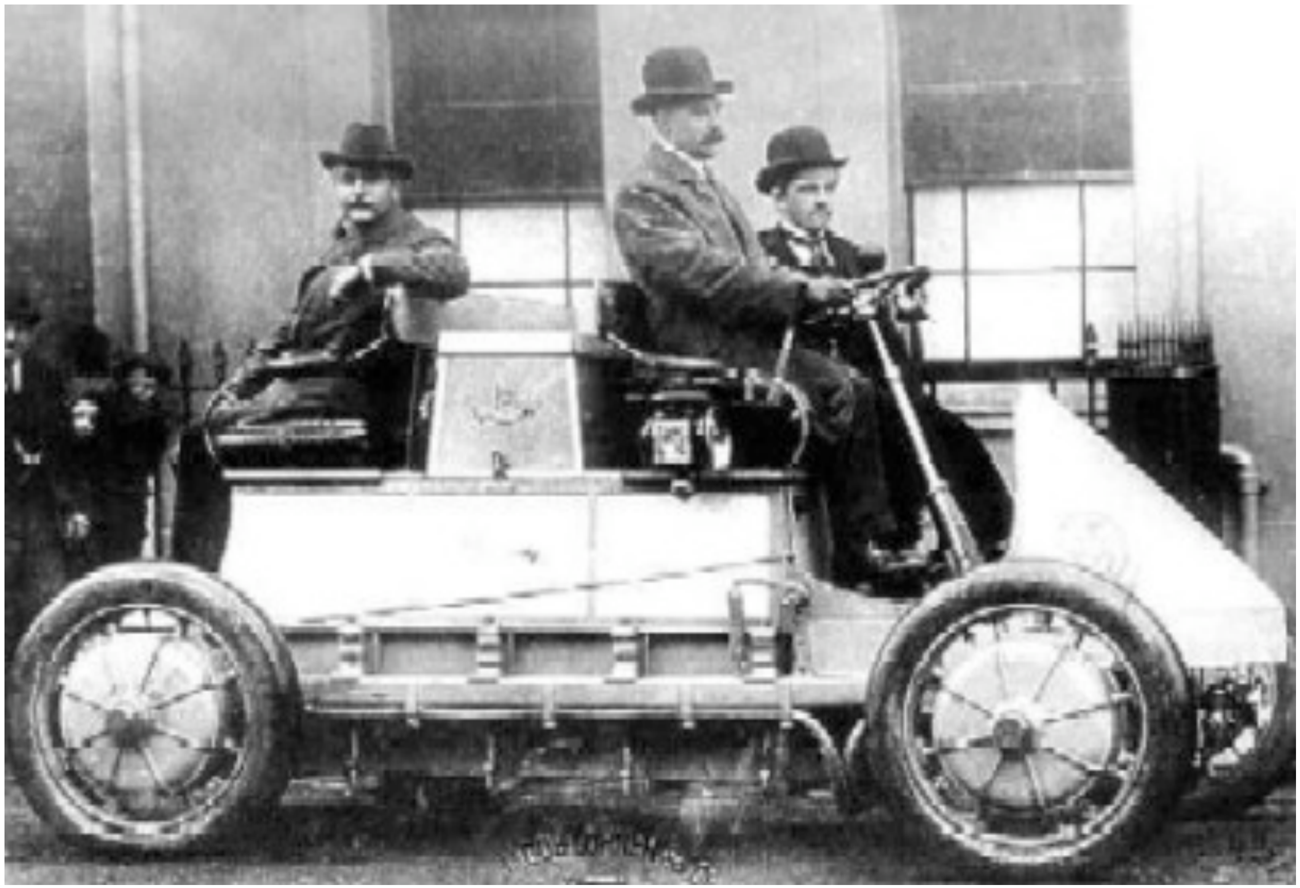
Early automotive history: non-Otto cycle engines

Hybrid gasoline-electric vehicles are not new

First hybrid 1901: to extend range, gasoline engine added to charge battery

Lohner-Porsche, hybrid "Mixte", top speed 35 mph. In-wheel motors on all four wheels – first four-wheel drive vehicle. 83% efficient at conversion of electrical-mechanical energy.

Figure: jalopnik.com



Also not new: linking together single engine, multiple motors

Hybrid technology in “land trains”: gasoline engine in lead car drives generator; electricity carried to each car to drive separate electric motors

Porsche “Landwehr”, post-1905 (while Porsche employed by Daimler), used by Emperor Joseph’s military to bring supplies to troops..

Figure: hybrid-vehicle.org

Transportation: steam also viable in personal vehicles

Design: Double-acting but closed system – water is condensed and re-used.

Advantages:

- Max torque at zero speed = no need for transmission
- Also no need to idle
- And lower speed engine –
- = less wear and tear
- Fewer moving parts
- Fuel supply often flexible.

Disadvantages:

- Heavier
- Slow to start

Figure: **1901** Kidder Steam Wagon. Kidder Motor Vehicle Co., CT (1900-1)

Transportation: steam cars persisted for ~30 years

Stanley Steamer: biggest selling U.S. car by 1899 (200 sold).

Burned gasoline or kerosene externally & made steam in vertical-tube boiler

Set world speed record in 1906 (128 mph). Production til 1927.

1911 Stanley Corp.
Model 72 20 hp
Roadster

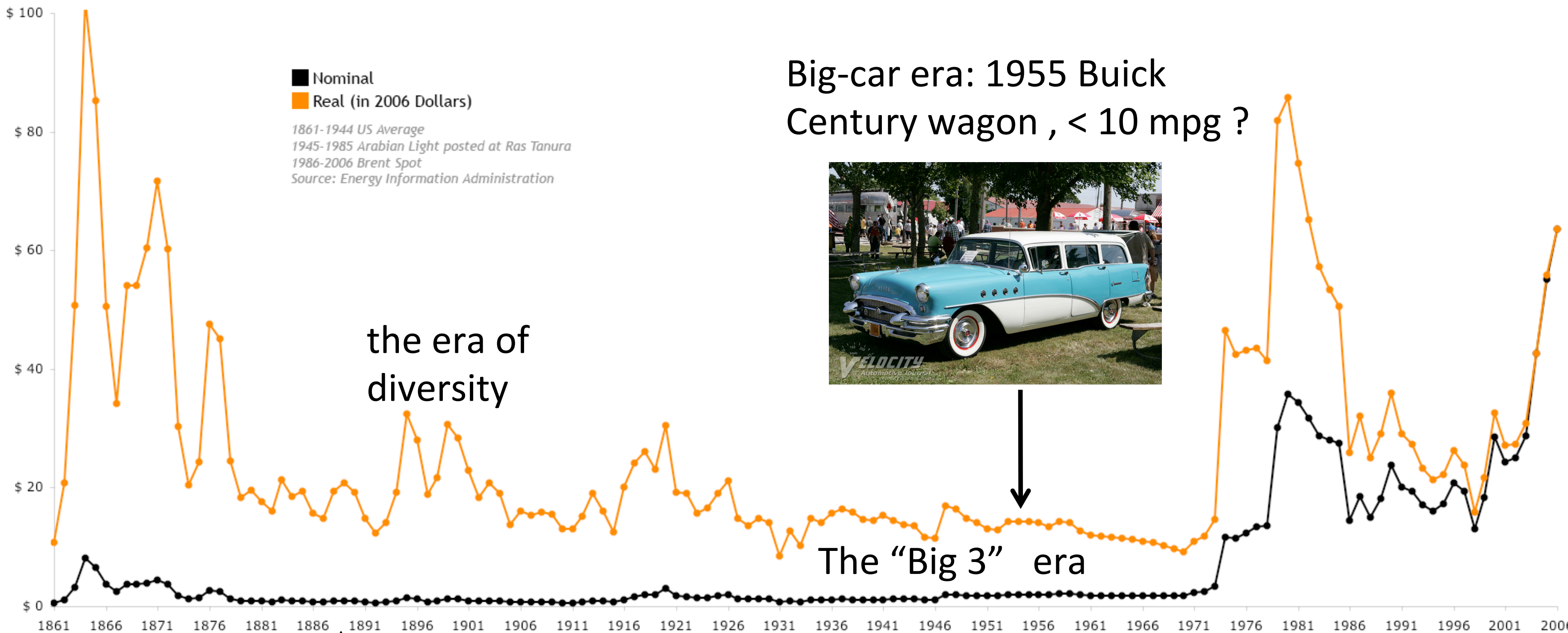
(Photo: Ken Hand)

History of autos summary: we've seen it all before….

- Innovation in engine fundamentals
- Multiple competing technologies:
  electric, gasoline, steam
- Hybrid gasoline-electric vehicles
- Multiple small car manufacturers with small production volumes
- Innovation as response to fuel prices or standards

Why did the internal combustion engine win out?

In part, because fuel became cheap…



the era of diversity

Big-car era: 1955 Buick Century wagon , < 10 mpg ?

The "Big 3" era

1888: Bertha Benz' drive

1908: Production of Model T Fords begins in Detroit

1973 oil shock
1973 Datsun 510

Fuel economy

Pitching small cars to the American people

required new approaches….

Fuel economy for cars and trucks follows federal standards

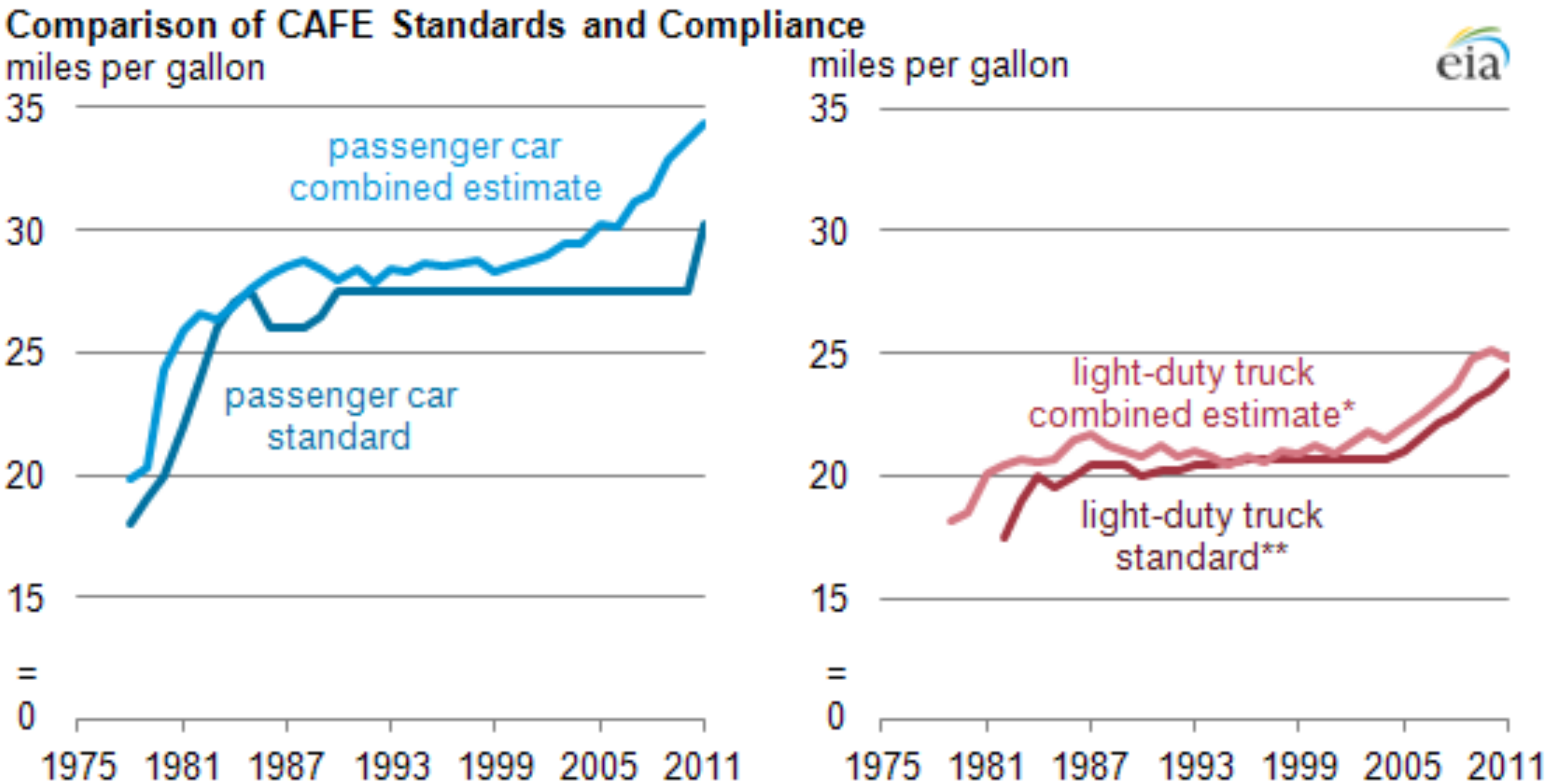
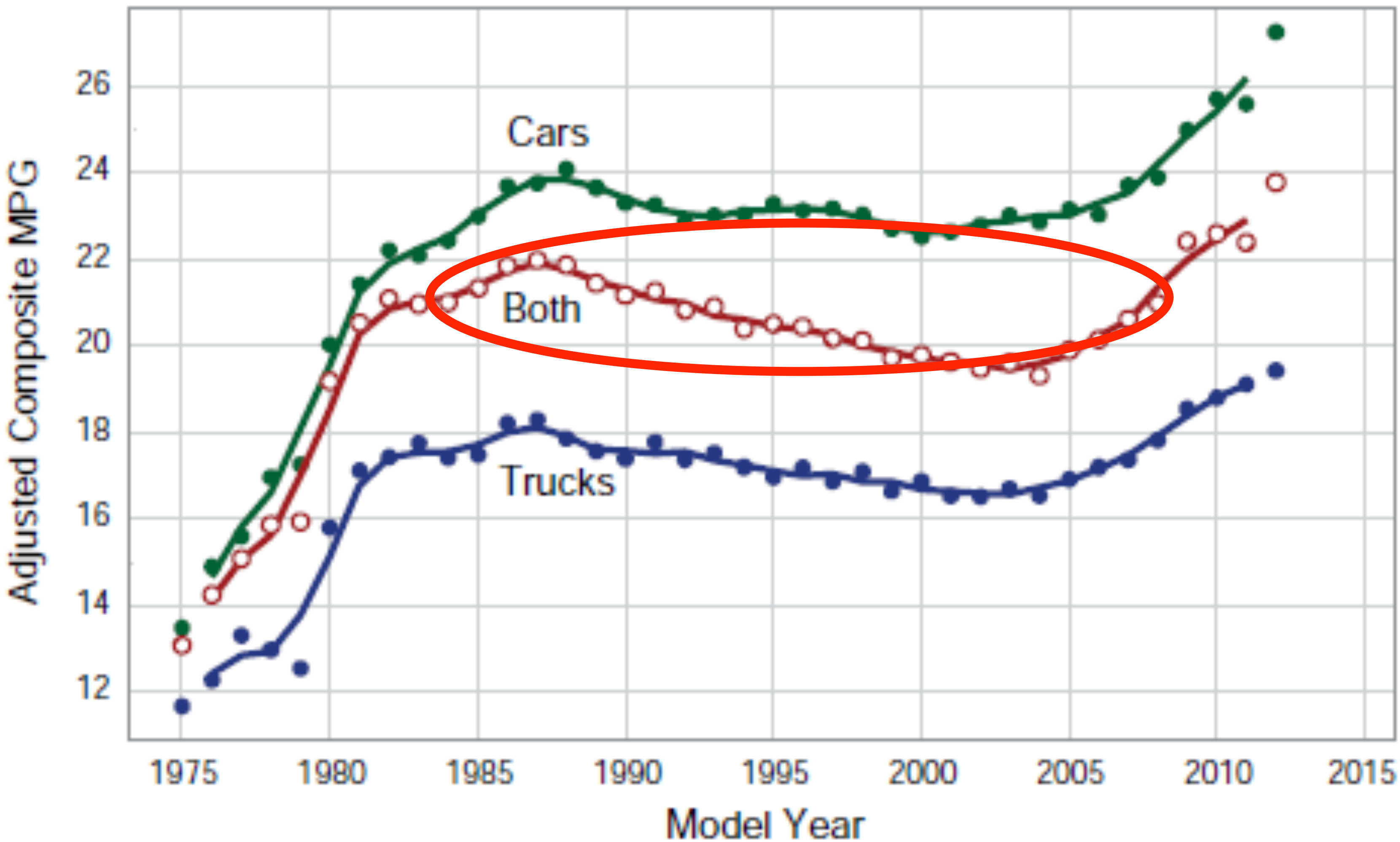


Figure: EIA

But note complications:

U.S. vehicles actually get worse in 1990s...

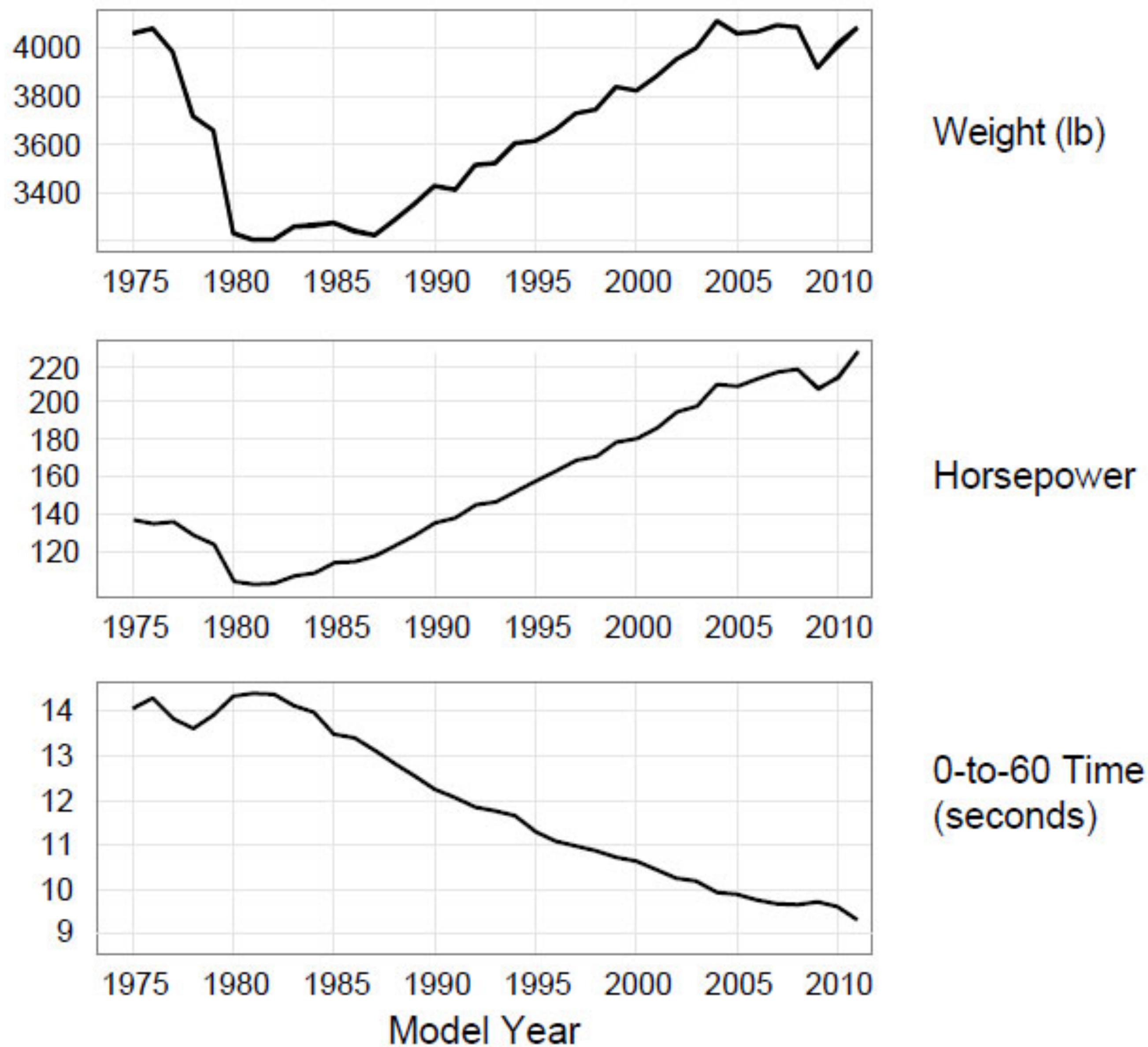


Why?

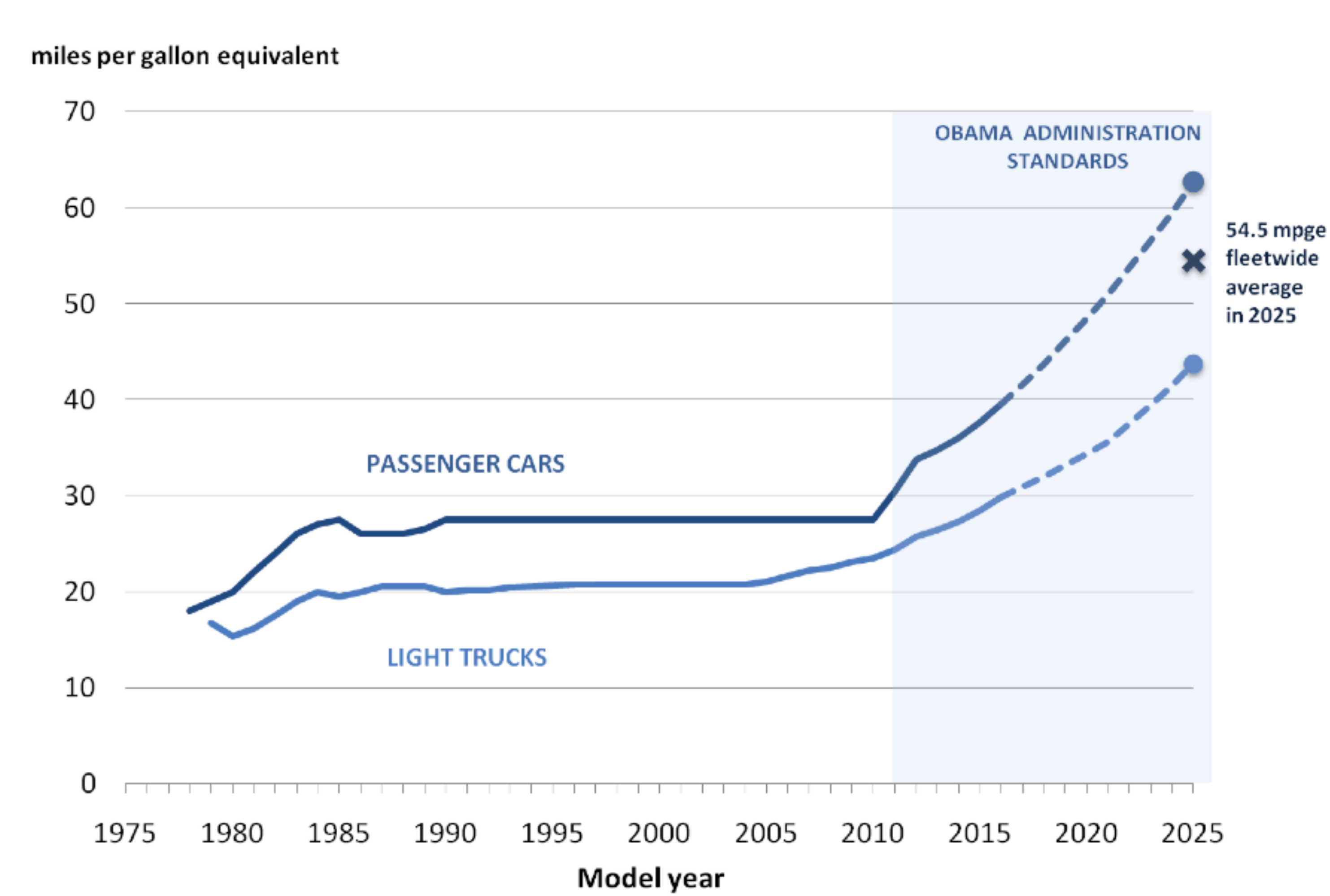
Increasingly people bought "trucks" instead of "cars"

Also: technological advances don't get used for fuel economy

technological improvements are used for other purposes



Obama standards are return to 70's era rates of change



MY1978-2011 figures are NHTSA Corporate Average Fuel Economy (CAFE) standards in miles per gallon. Standards for MY2012-2025 are EPA greenhouse gas emission standards in miles per gallon equivalent, incorporating air conditioning improvements. Dashed lines denote that standards for MY2017-2025 reflect percentage increases in Notice of Intent.

Little publicity or protest: endorsed by automakers, UAW, etc.
Will they be met by reducing weight, reducing performance ... or real innovation?

What governs fuel usage?

What happens to the fuel burnt in a car engine?

ENGINE

Typically ~ 25% efficiency) in Otto, 30% in Diesel

(that is, 25-30% fuel energy → kinetic energy)

So ~ 75-70% loss to heat

What then happens to the kinetic energy?

Must dissipate somehow and eventually also become heat

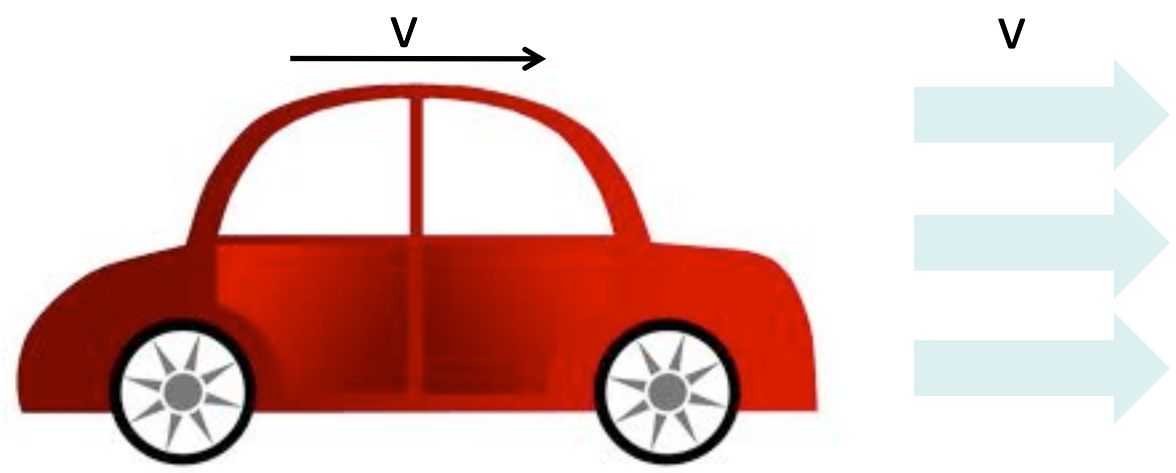
DISSIPATION

Roughly equal in size:

1. **Braking** (kinetic energy must be replaced later on acceleration)
2. **Frictional losses in gears, bearings**
3. **Rolling resistance**
4. **Air resistance** (aerodynamic drag)

Fuel uses in transportation: air resistance

Energy used to push air in front of car – goes into kinetic energy of the air



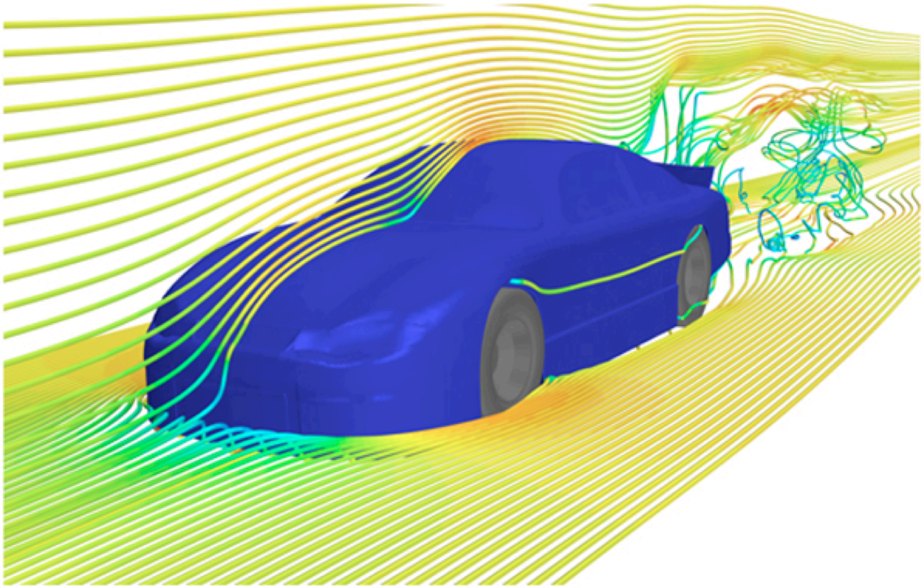
Worst-case scenario: the car pushes all air it intersects up to its speed v. Power to do this is same as energy in flow of air at that speed:

$$P = \frac{1}{2} \rho A v^3$$

where A is the cross-sectional area of the car.

Fuel uses in transportation: air resistance

Real life is not the worst-case scenario – car slips through air without having to accelerate it all to v



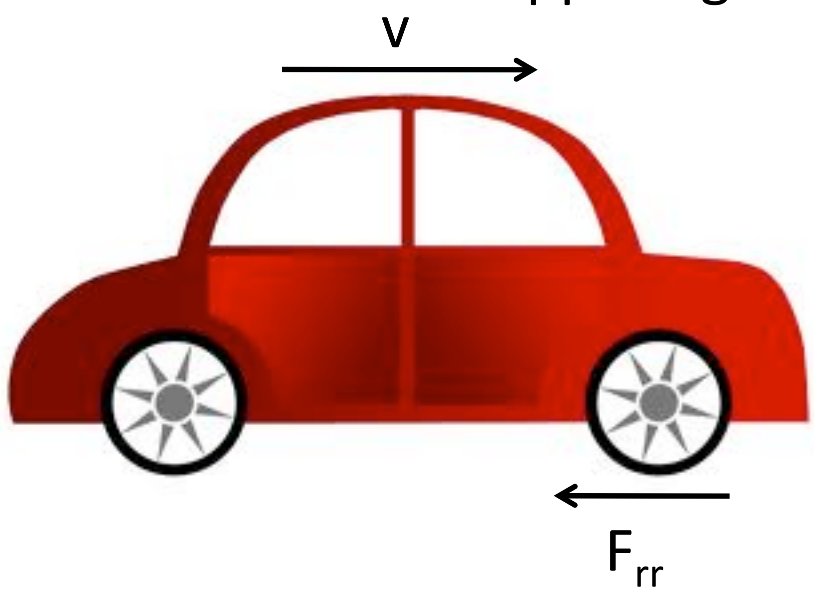
Solution: adjust formula by some fudge factor that describes how "streamlined" the car shape is:

$$P = C_a \, ½ \, \rho \, A \, v^3$$

Sports cars want low C_a because of v^3 depend. Typical C_a: Porsche 0.3, Hummer 0.6.

Fuel uses in transportation: rolling resistance or "rolling friction"

In real deformable tires, friction between tires and road causes force opposing motion of the car.



Fuel uses in transportation: rolling resistance or "rolling friction"

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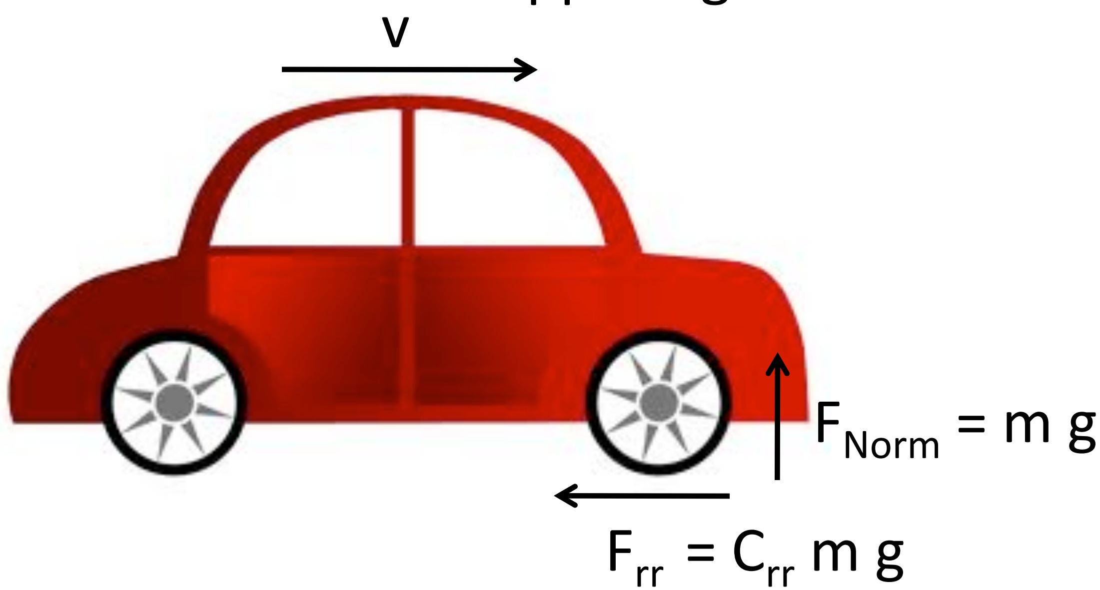


Force of rolling friction is proportional to normal force that opposes car's weight against ground.

(Stick in a constant C_{rr} , the "coefficient of rolling resistance")

Power dissipated is energy/time = force x distance / time :

$$P = C_{rr}\, m\, g\, v$$

Rolling resistance

Value of C_{rr} depends on tire and surface properties – including deformability of tires

Approximate C_{rr} values

Steel wheels on steel rails	.001
Car tires on concrete	.01
Car tires on asphalt	.03
Car tires in sand	> .1

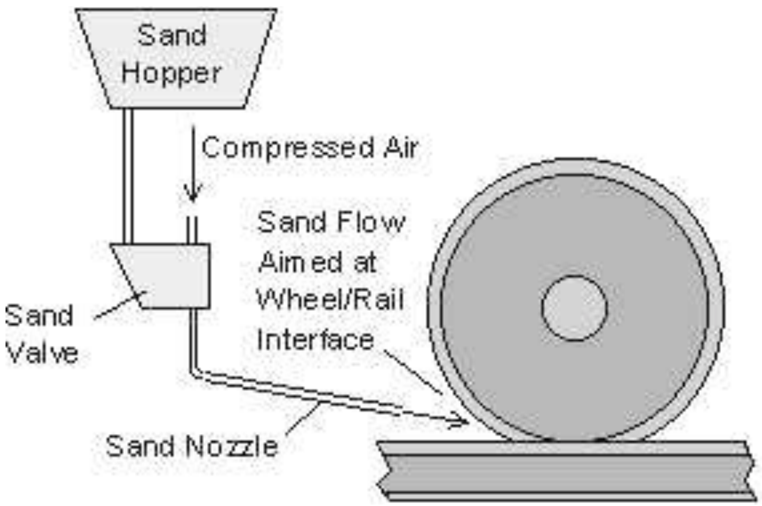
Steel rails are slick – low friction – so low rolling resistance, great for minimizing power losses in long-distance travel.

But problematic for starting up or stopping suddenly, when torque must be high. Need some friction to apply torque to the wheel, or just spins in place.

Trains needs some solution that combines efficient long-distance travel with ability to brake and start.

Sand provides as-needed increases in friction for train tracks

Sand is released through nozzle onto tracks when traction needed



Sanding system
Image: Univ. of Sheffield

Sanding nozzle
Image: HowStuffWorks

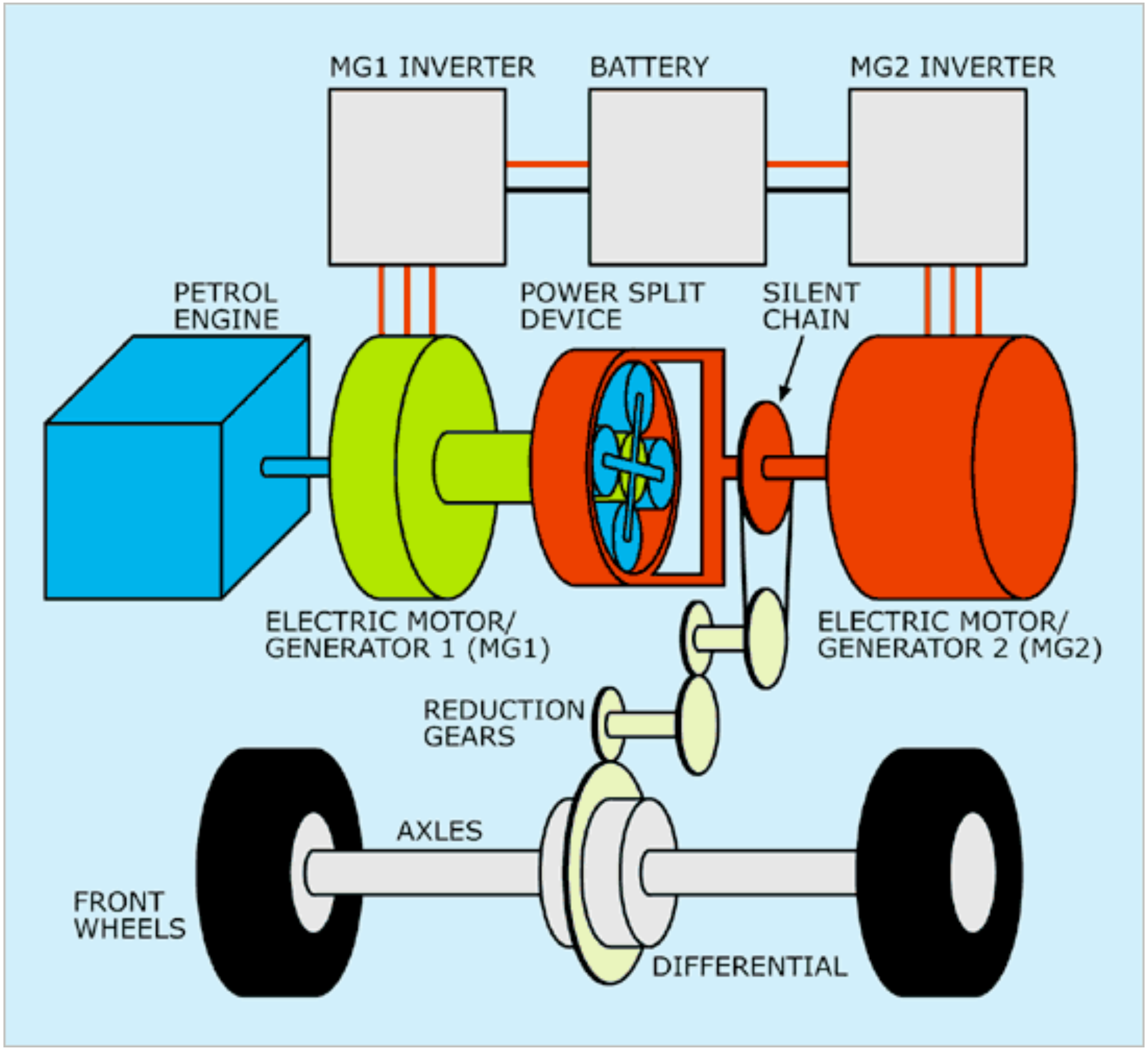
Sand temporarily increases friction (and so also C_{rr})

New (old) automotive technologies

Hybrid automobiles: most commercial are parallel hybrids

Toyota Prius uses AC motors and generators. Not only does it needs a transmission and drivetrain, it requires 2 inverters + a power split device to allow power from both gasoline and electric motors at once.

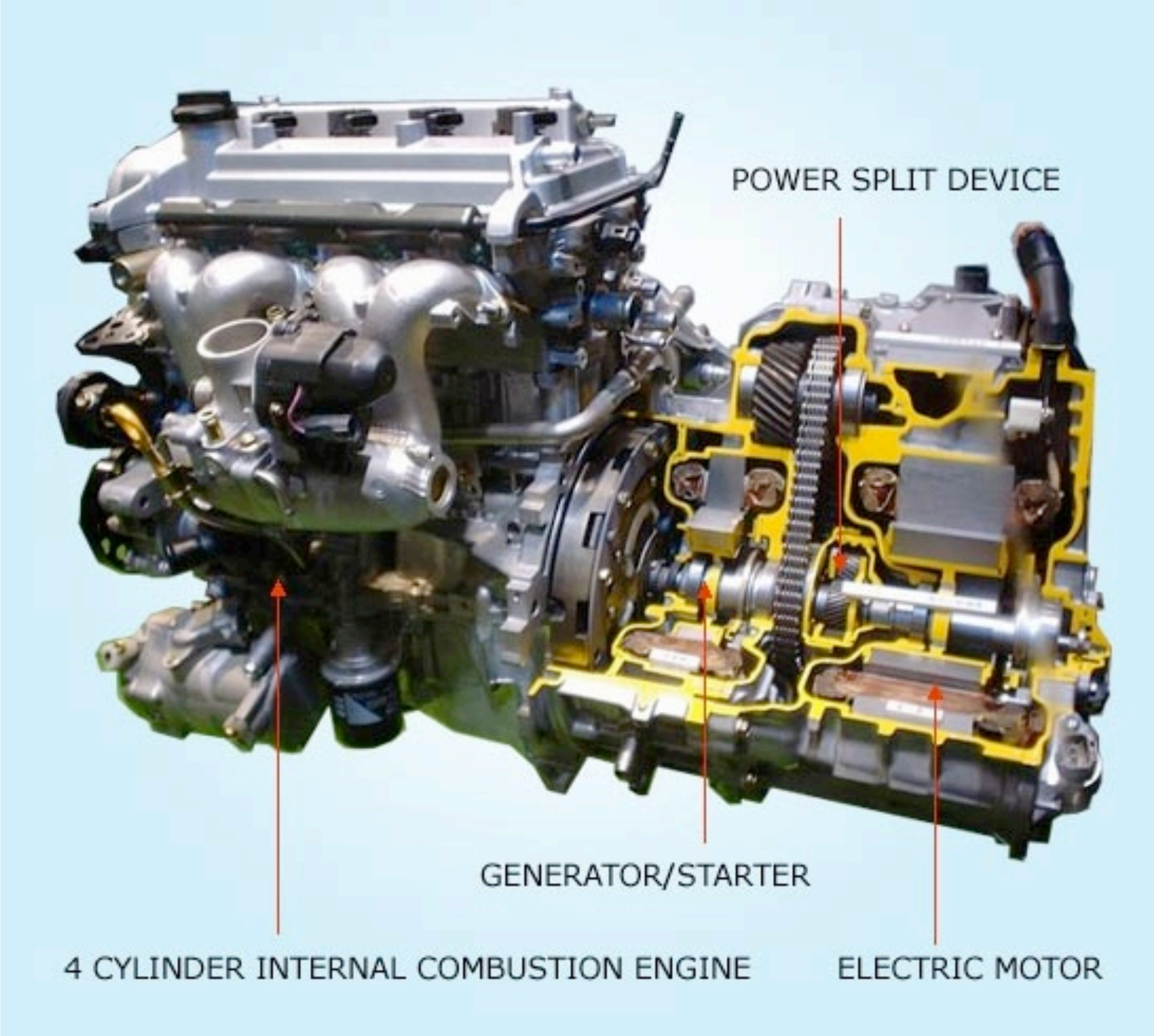
Figure: CleanGreenCar



Parallel hybrids: "power split device" fantastically complicated

Toyota Prius engine

Figure: CleanGreenCar



Why are automobiles parallel and not series hybrids ?

"So the choice seems clear. If you want a product that's easy on the environment, gets great fuel economy and has good performance, the only reasonable choice is Hybrid Synergy Drive. You can buy a vehicle powered by the system right now, today. But if you want a series hybrid, well – you can cross your fingers and wait for a few years until some difficult engineering and production problems are solved. Or, you can look into buying a locomotive."

Irv Miller

Group Vice President, Corporate Communications, Toyota

defending Toyota's choice of parallel vs. series hybrid for the Prius