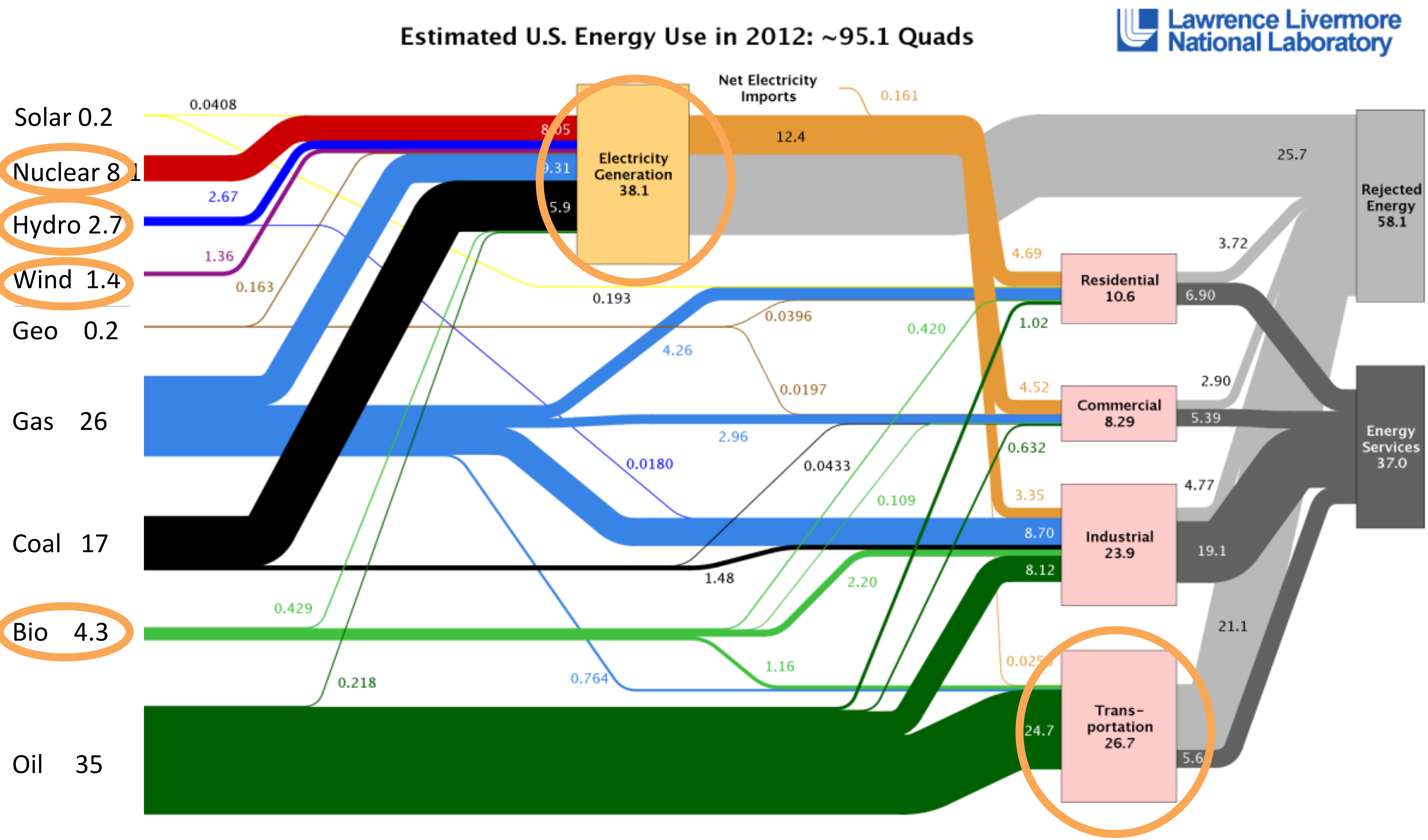
GEOS 24705 / ENST 24705
Internal combustion engine and transportation II

U.S. energy use, 2012

Done or begun



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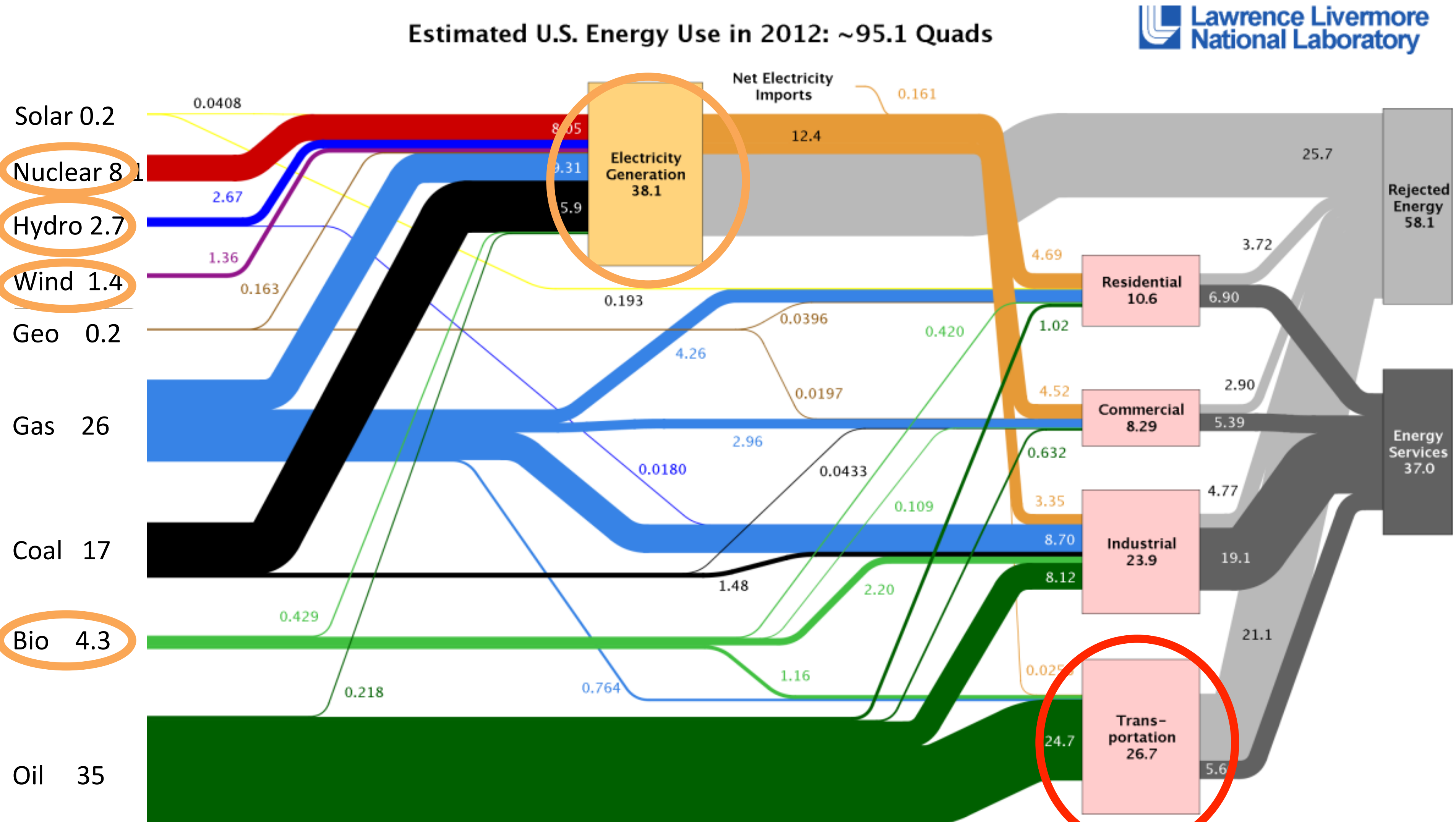
U.S. energy use, 2012

Today



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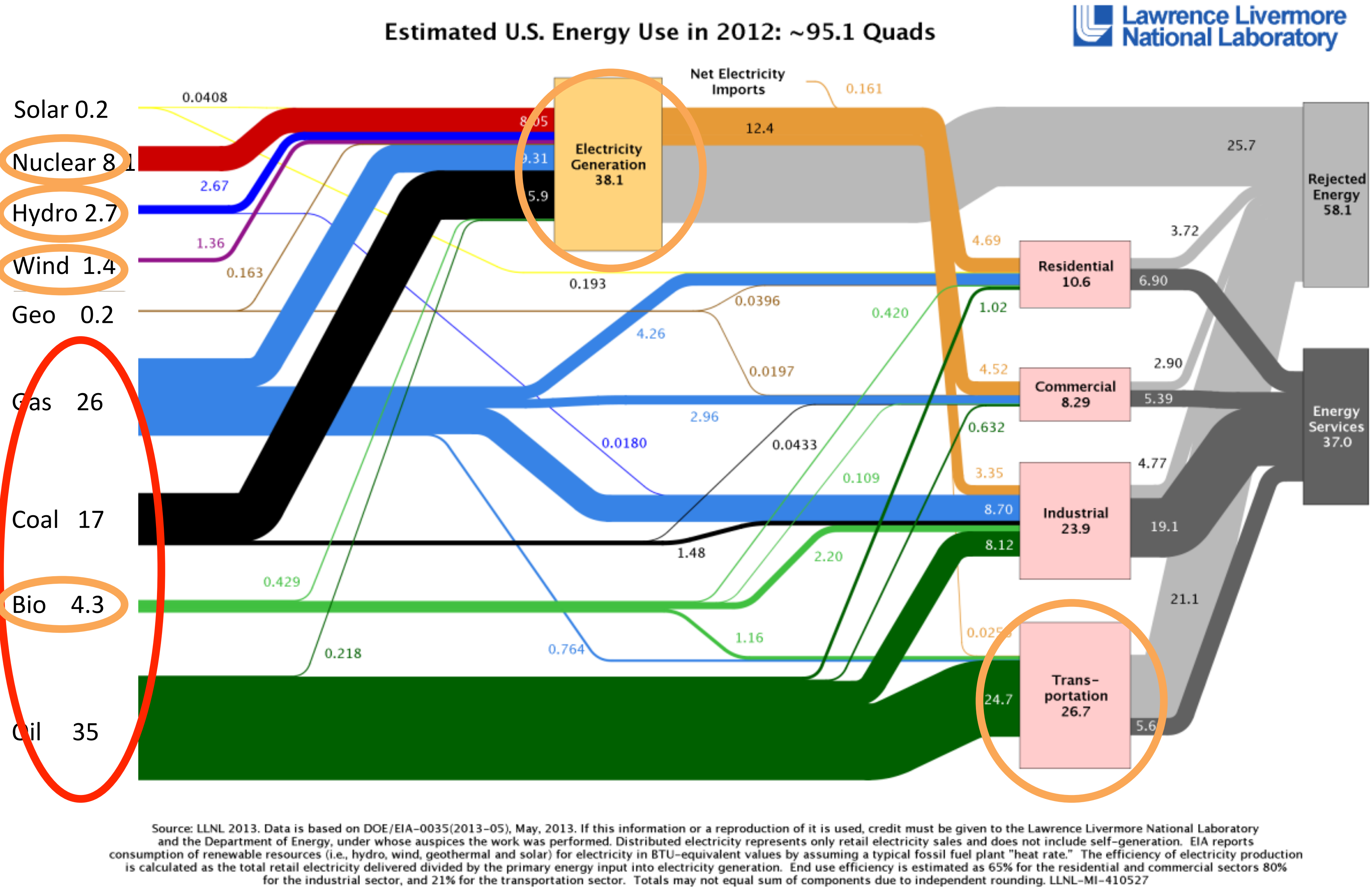
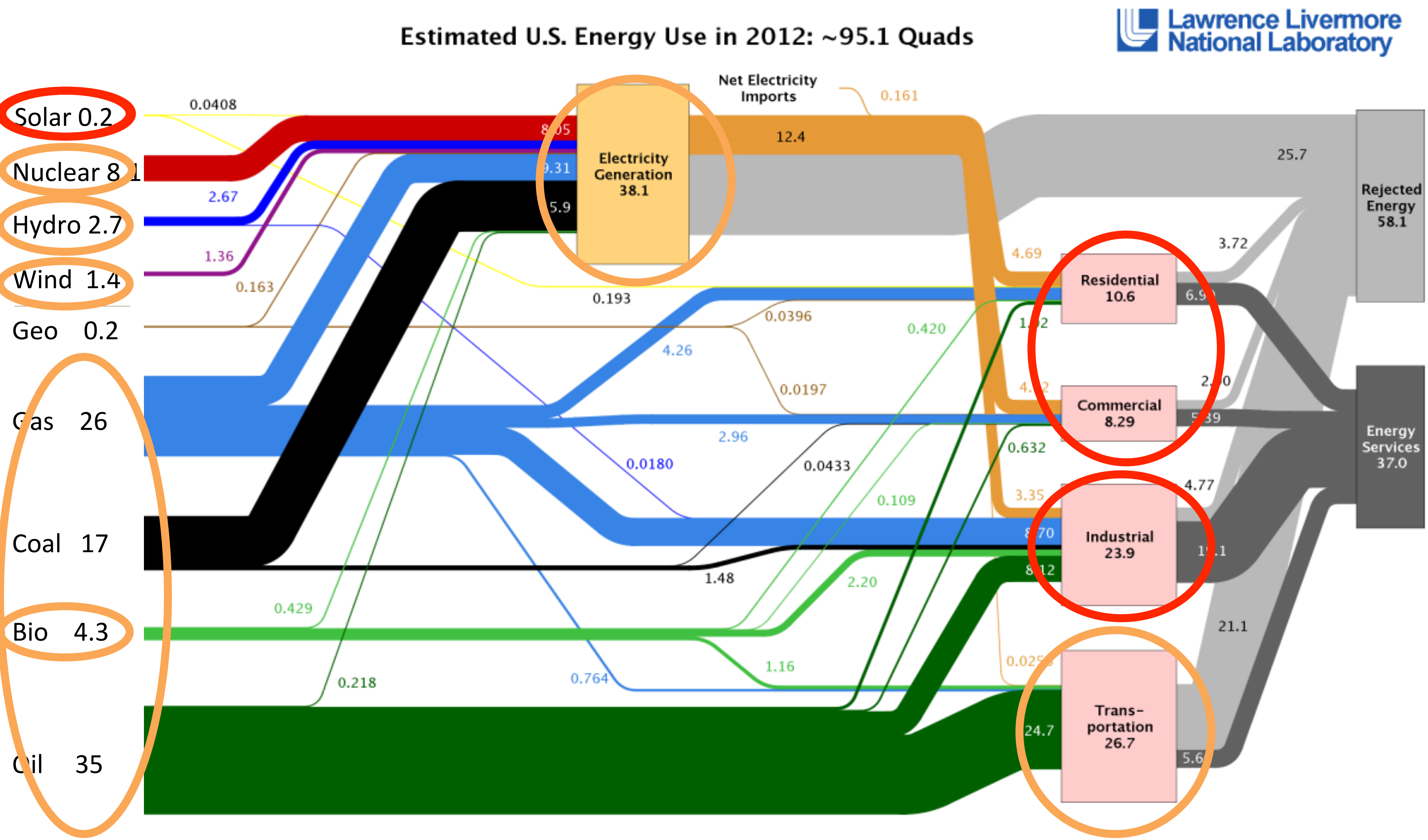
U.S. energy use, 2012

Thursday



U.S. energy use, 2012

Next week



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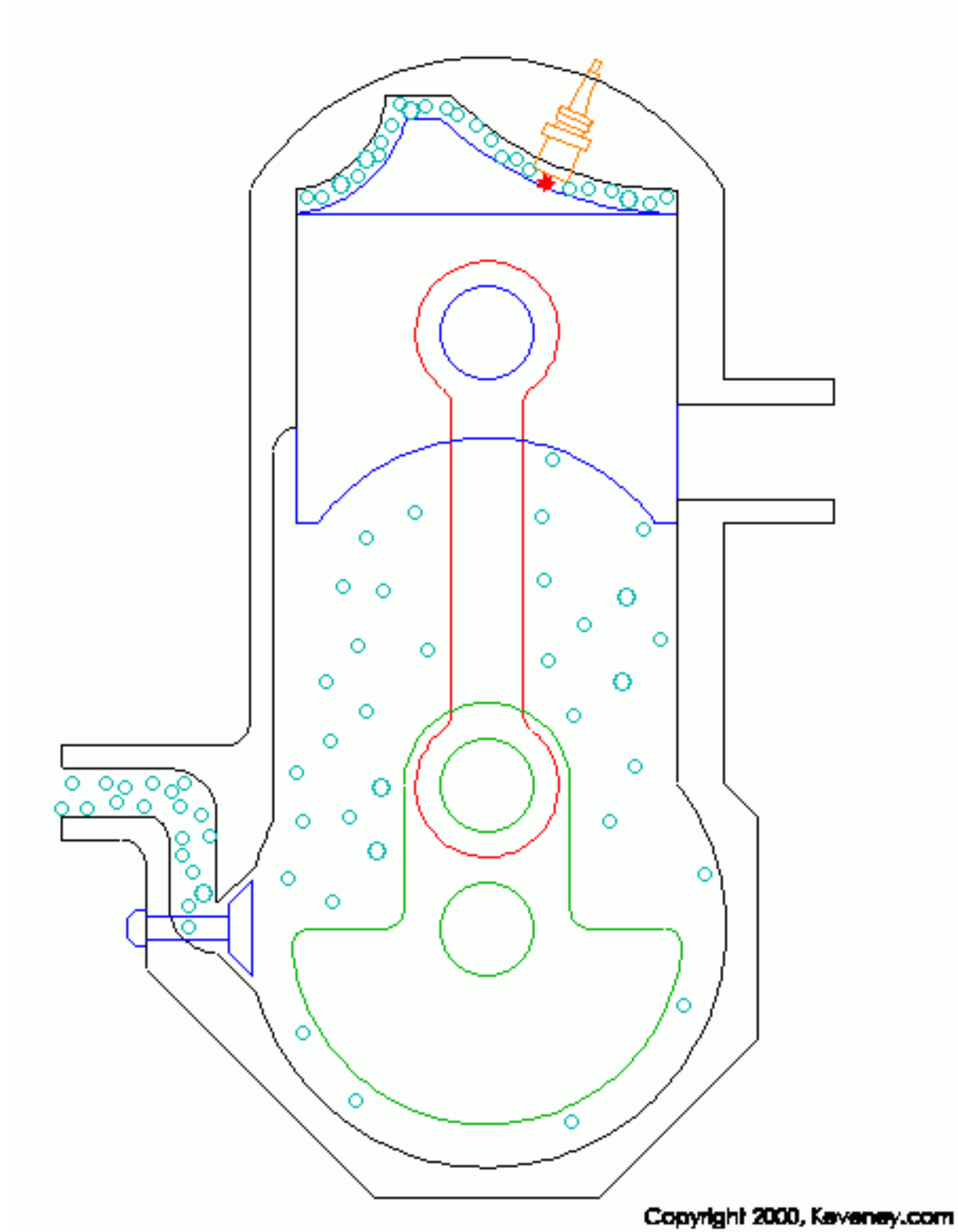
Four-stroke engines: Otto cycle

Two-stroke engine: Otto cycle

Preparation and power in one cycle *(down/up)*

1. Compression while unburnt fuel fuel is drawn into crankcase

2. Ignition followed by expansion while exhaust leaves cylinder AND fuel/air mixture enters cylinder

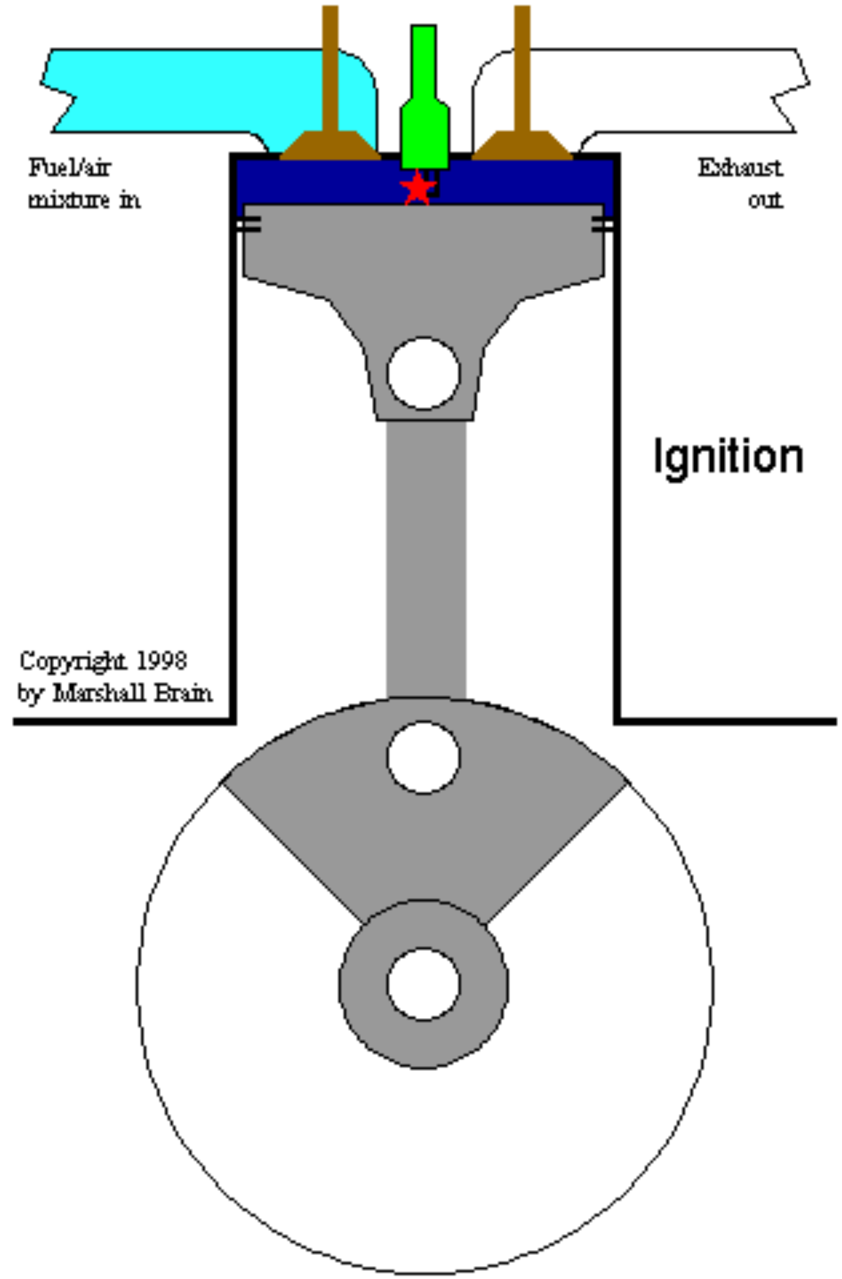


Four-stroke engine: Otto cycle

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

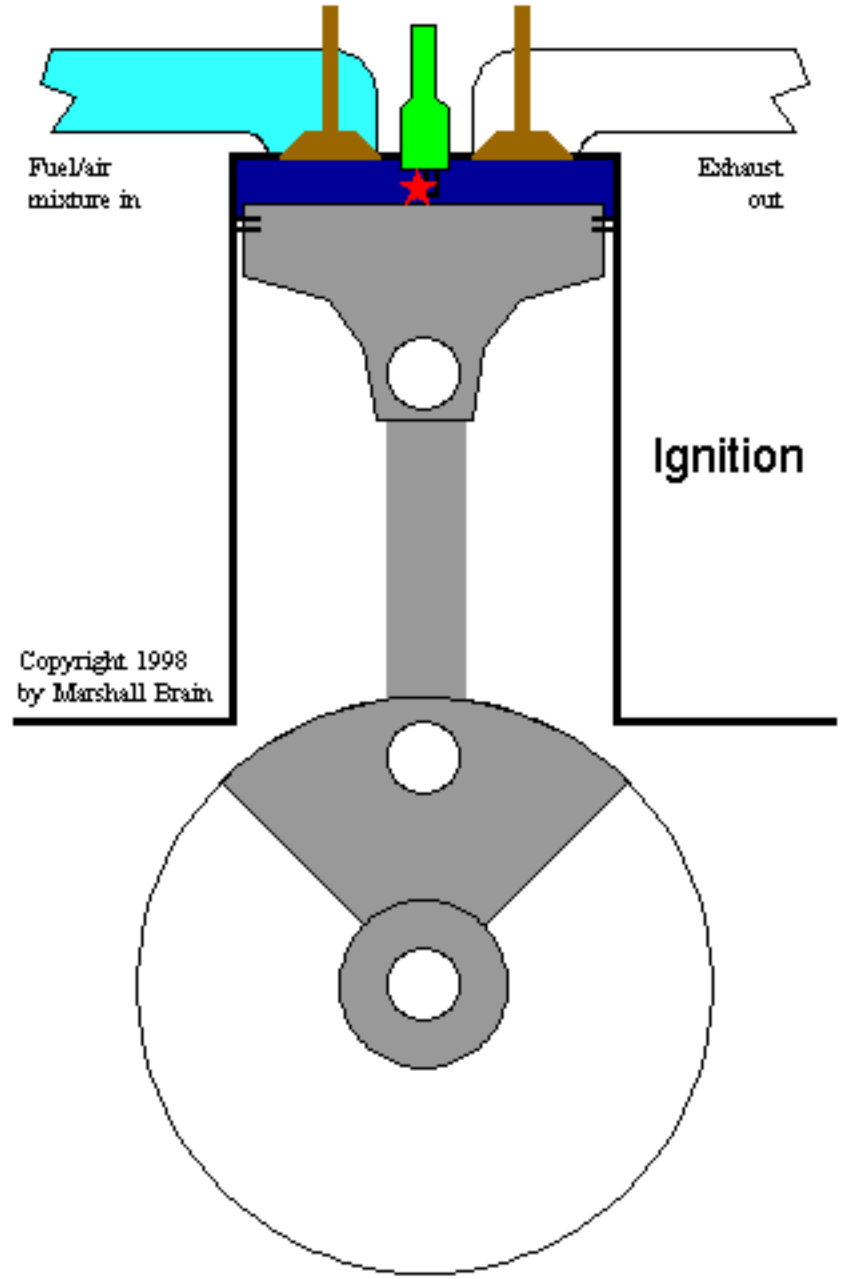
1. Intake
2. Compression
3. Combustion
4. Expansion *(Exhaust)*

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 before combustion

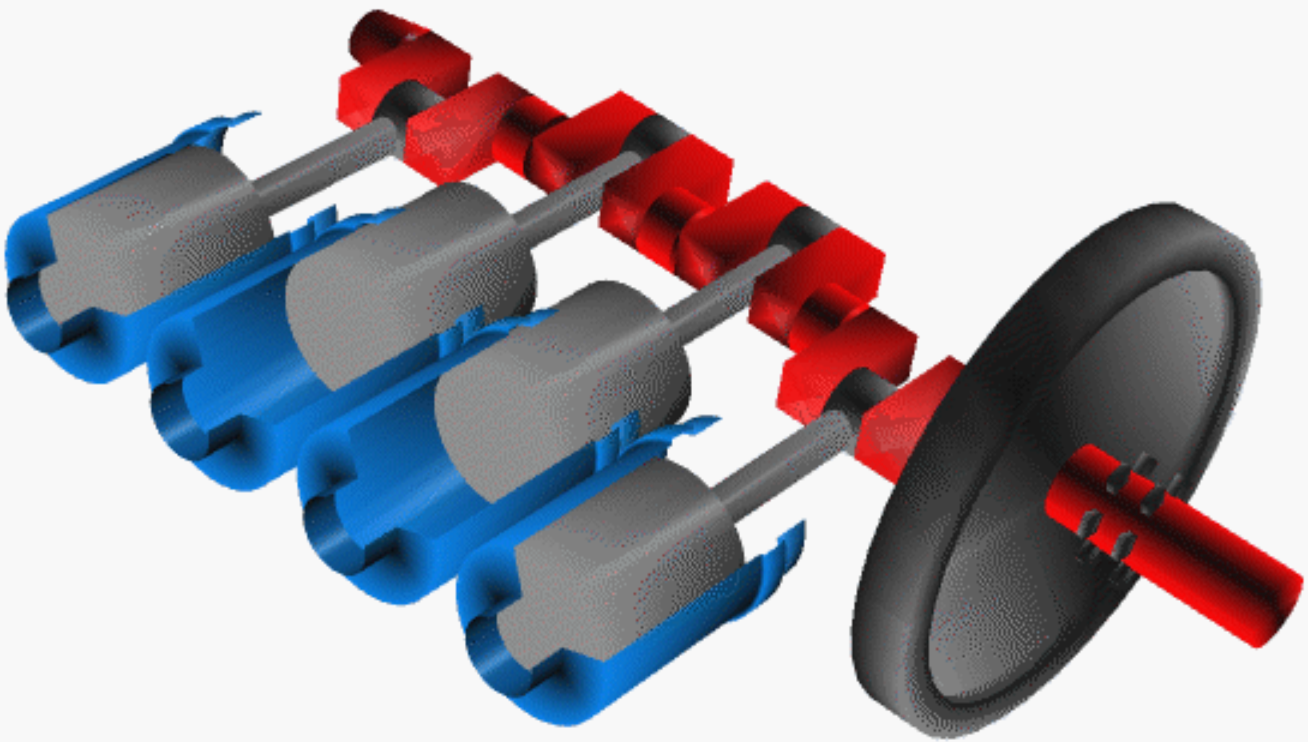
Separates unburnt fuel/air from combustion cycle

Disadvantages:

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

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)

Early automotive history: non-Otto cycle engines

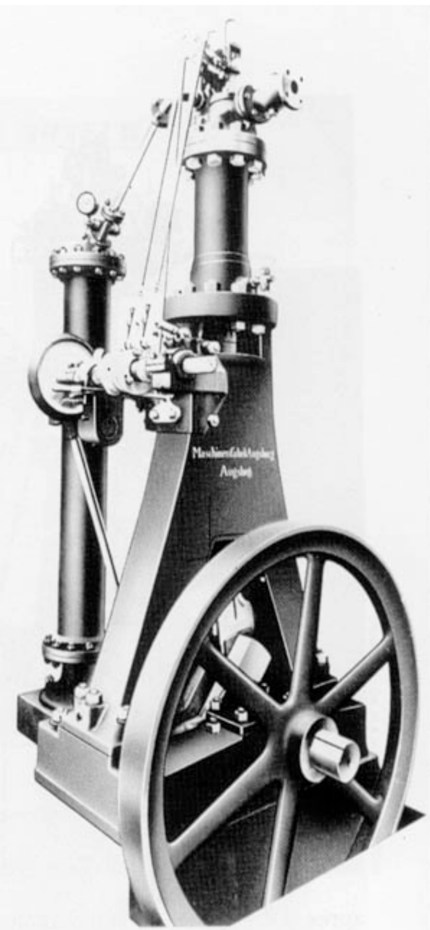
Engine history: *non-Otto-cycle engines*

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

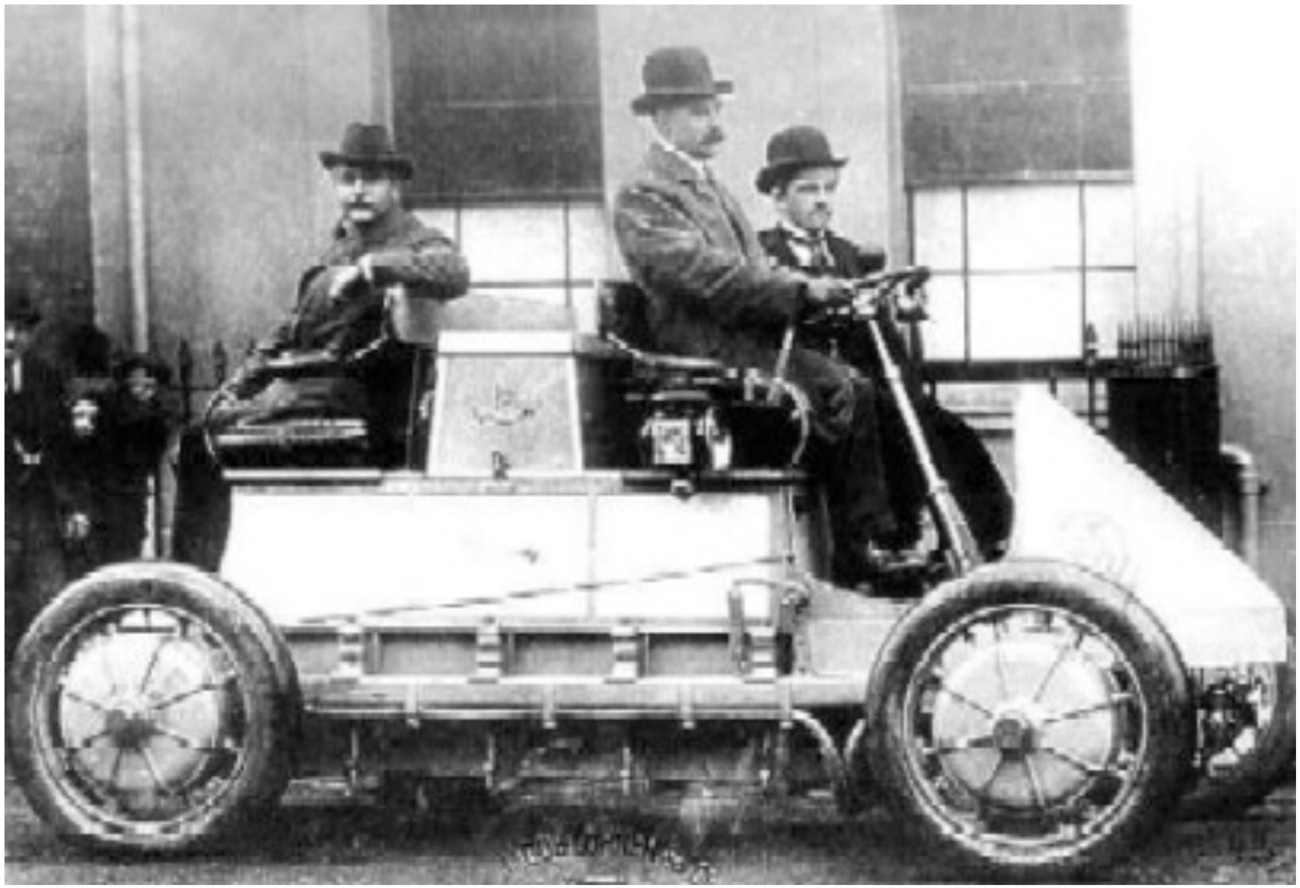
Lohner-Porsche Elektromobil, designer: Ferdinand Porsche, Austrian, age 24. Note electric motors in front wheels.

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

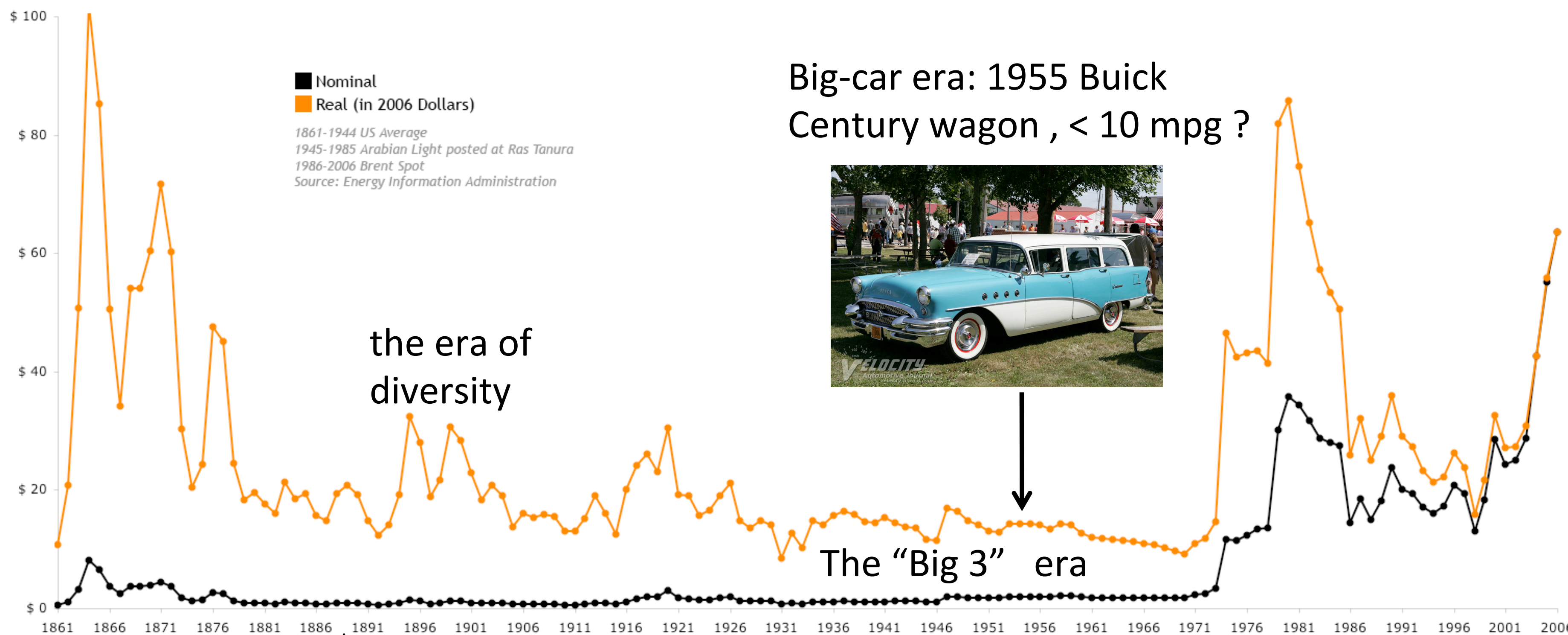
- Multiple competing technologies:
  electric, gasoline, steam
  hybrid gasoline-electric cars!

- 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…



1888: Bertha Benz’ drive

1908: Production of Model T Fords begins in Detroit

1973 oil shock
1973 Datsun 510

Some drawbacks of the ICE

- Engine speed mismatched to wheel speed

  → *requires transmission*

- Single power system

  → *requires drivetrain*

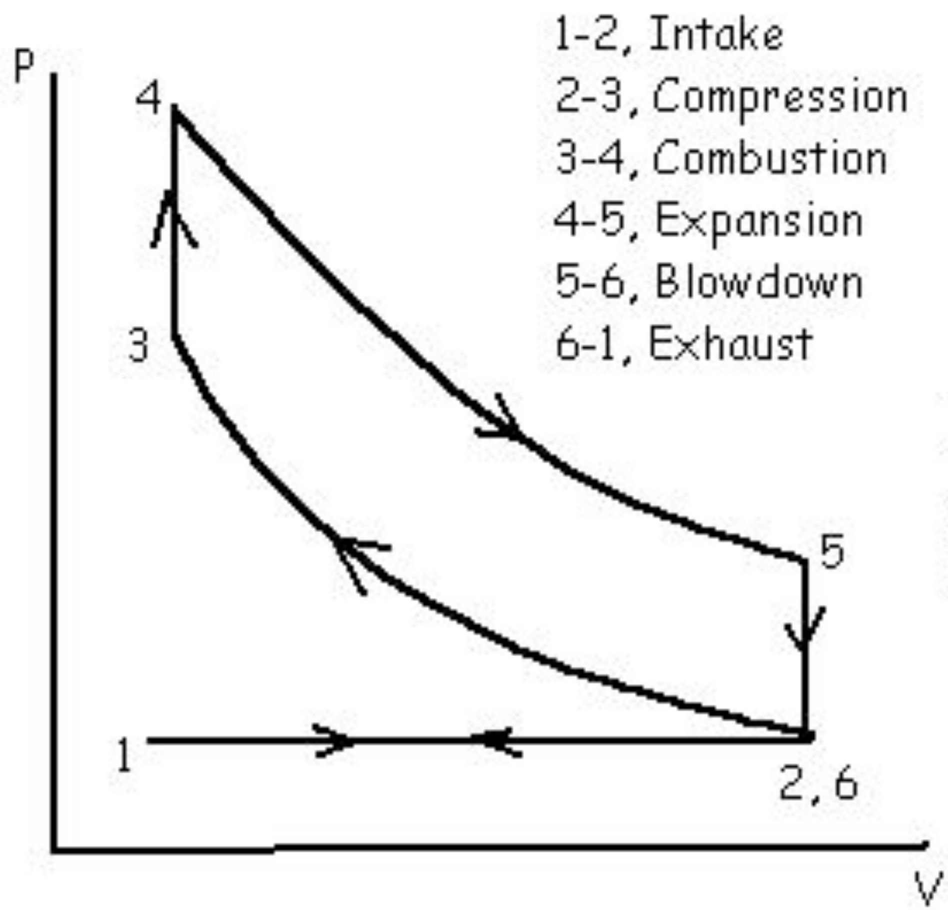
- Single power system but wheels must rotate at different rates (when going around curves)

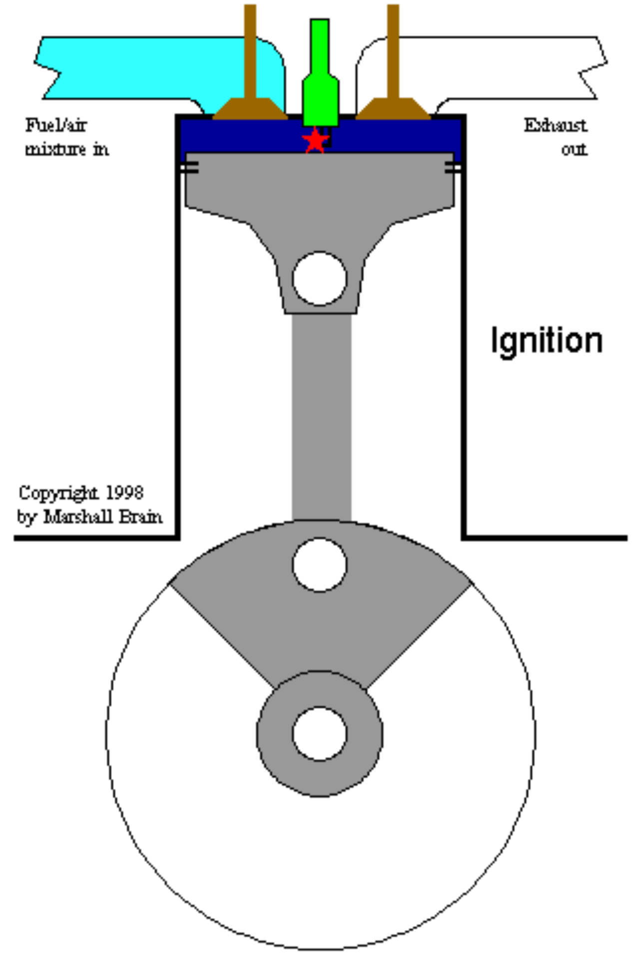
  → *requires 'differential'*

ICE thermodynamics and characteristics

Thermodynamic cycles: Otto cycle

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



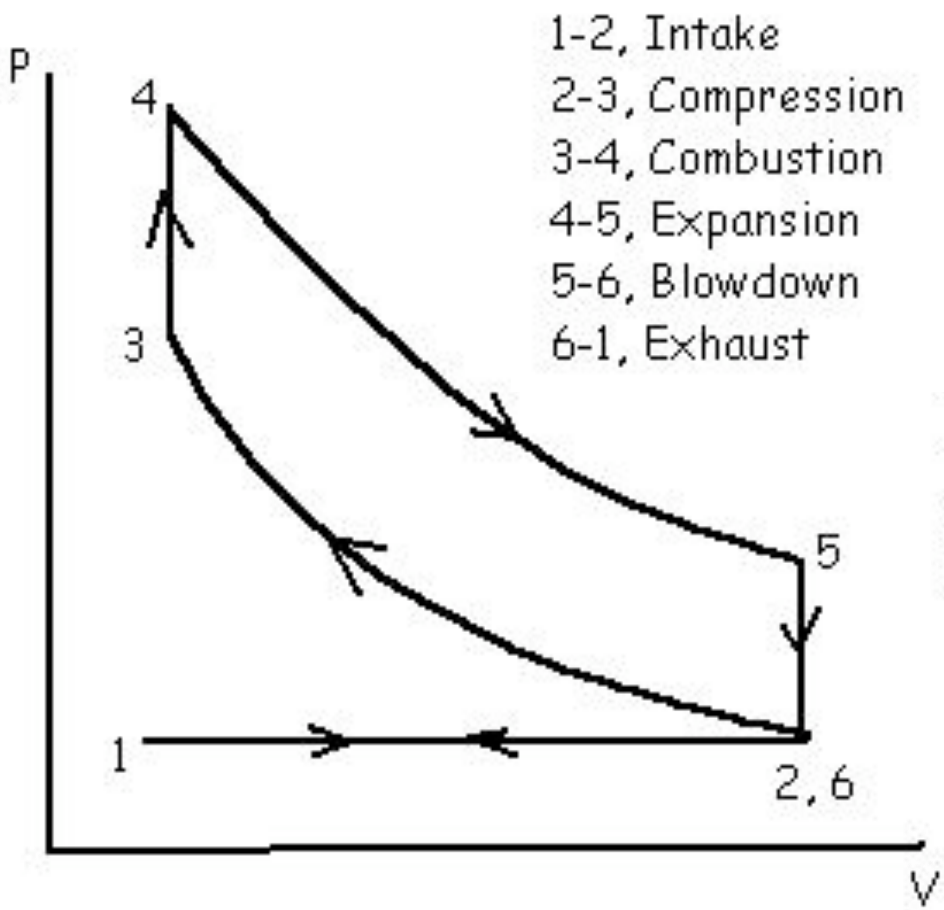


ideal Otto efficiency = $1 - (1/r)^{\gamma-1}$ where r = compression ratio V_1/V_2

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

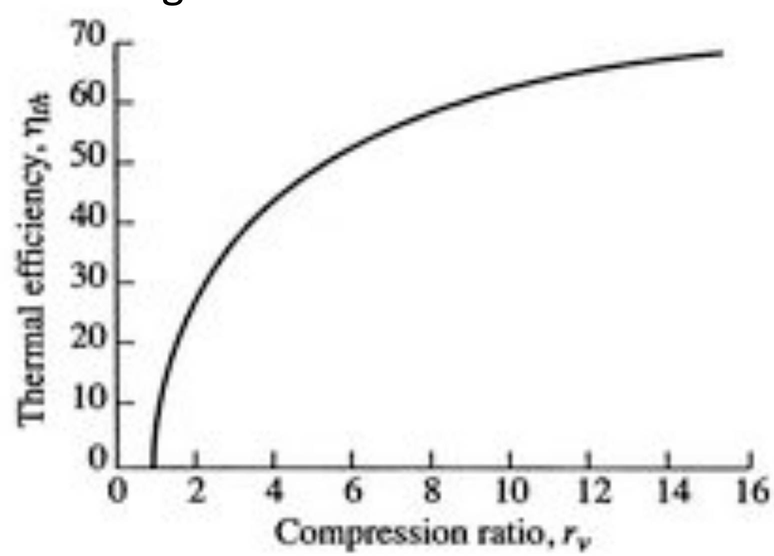
Thermodynamic cycles: Otto cycle

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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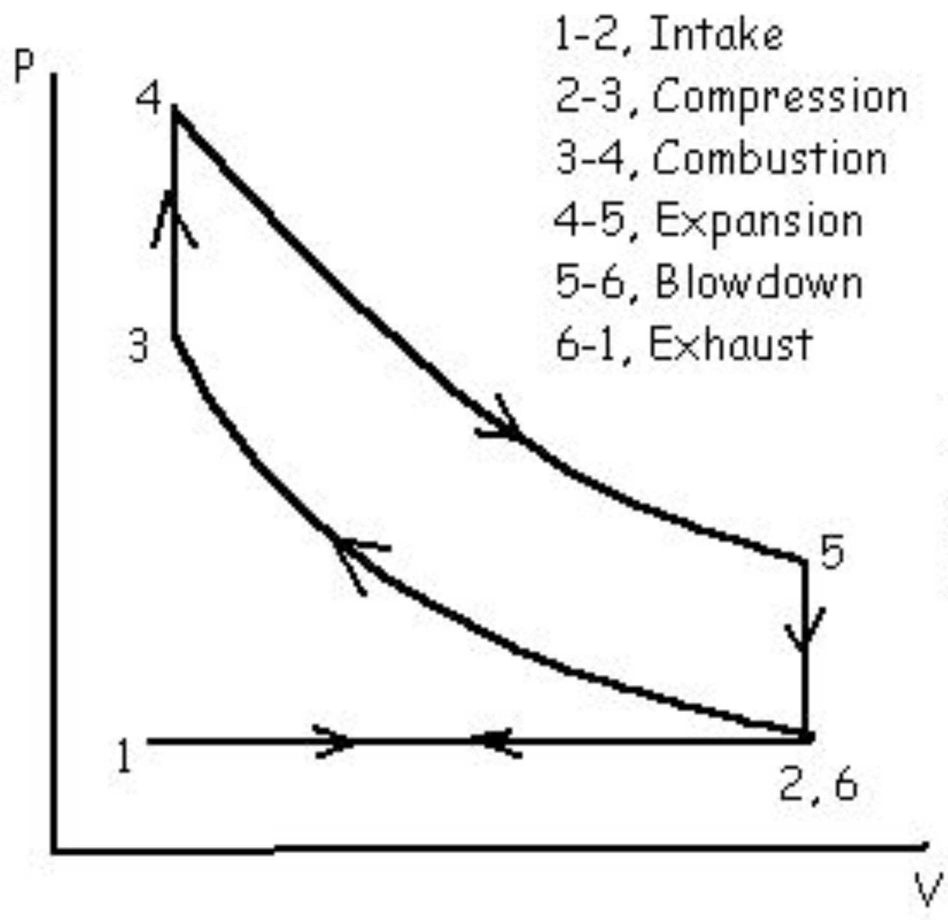
Thermodynamic cycles: Otto cycle

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...



Thermodynamic cycles: Diesel cycle

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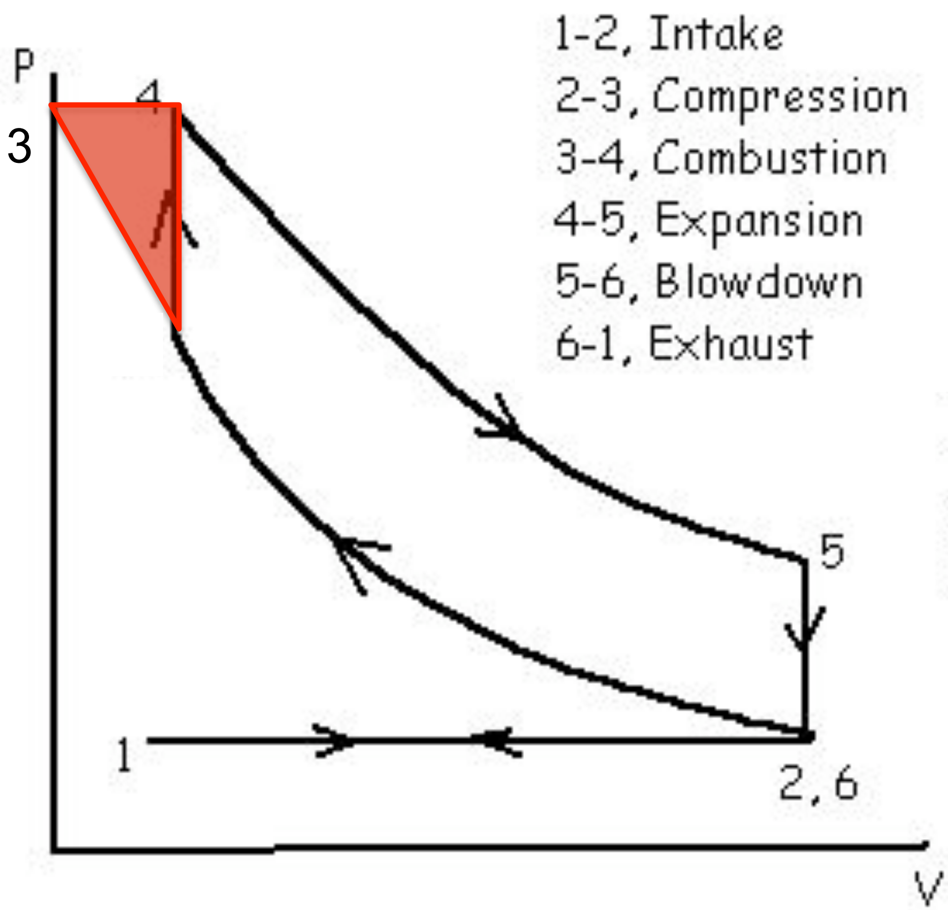


Diesel cycle involves

- higher pressure
- lower final volume

→ higher compression ratio

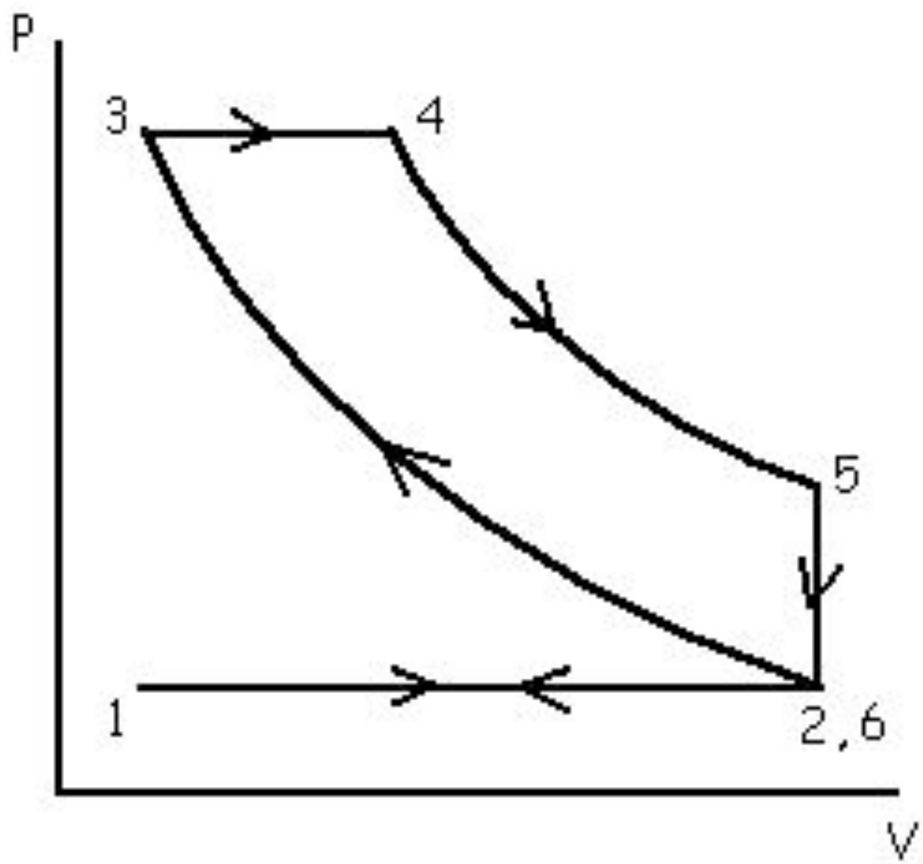
r ~ 14 – 22 or more

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

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

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.

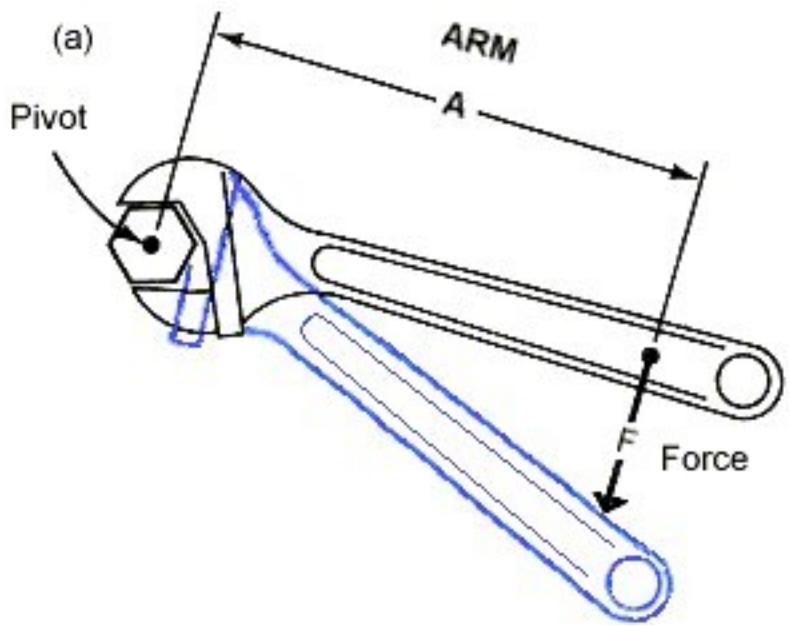
   Pollution problem greatly fixed in recent engines

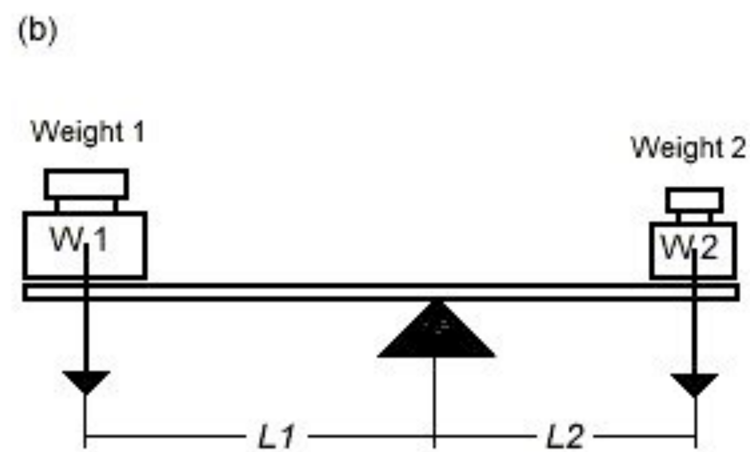
Different Ways to Turn Wheels: Otto, Diesel, Others?

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





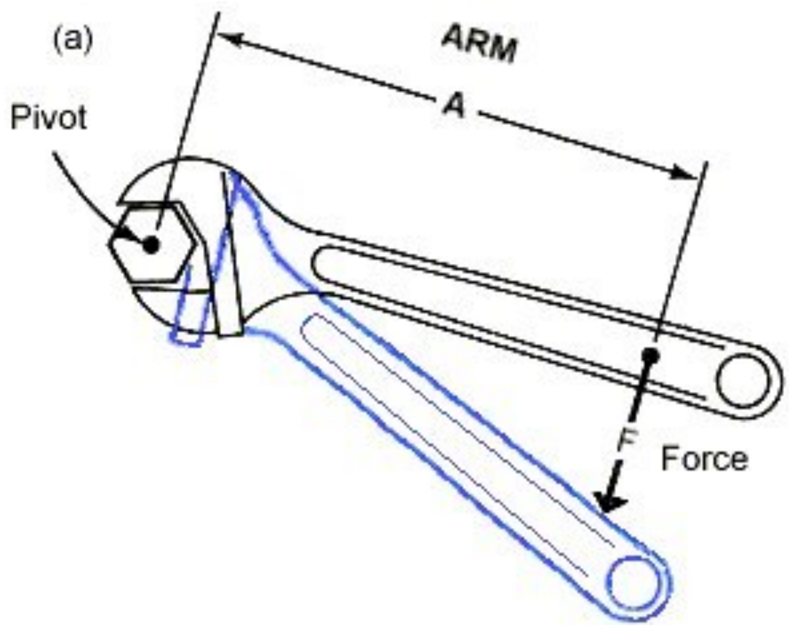
Power = energy/time

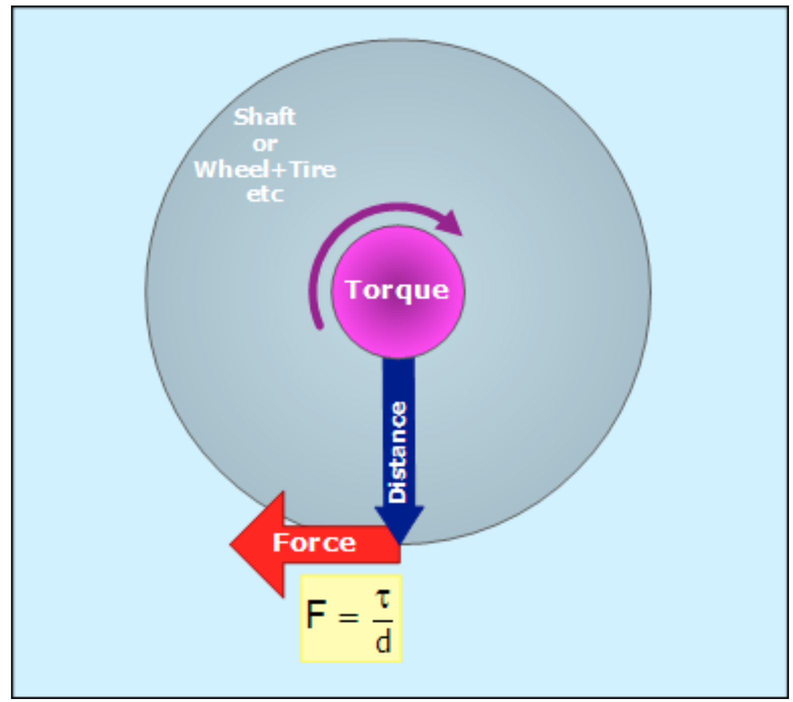
= **torque x rotation rate (P = τ x ω)**

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

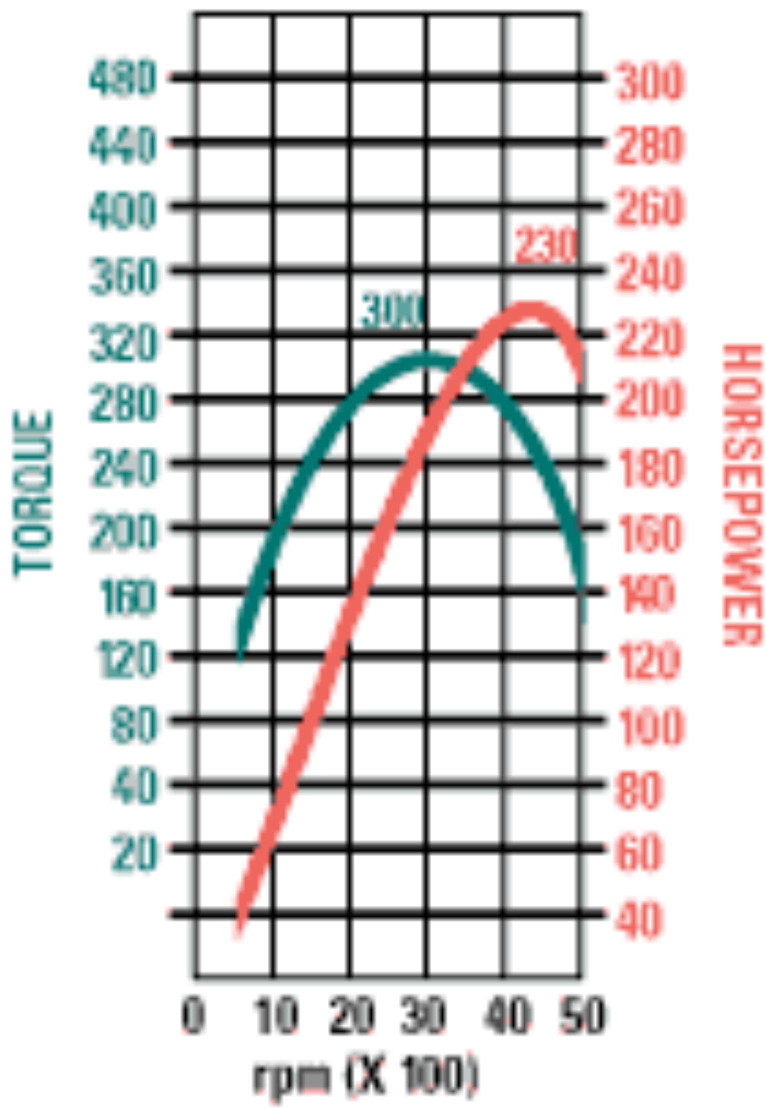




Power = energy/time

= torque x rotation rate (P = τ x ω)

NO internal combustion engines runs well at slow speeds



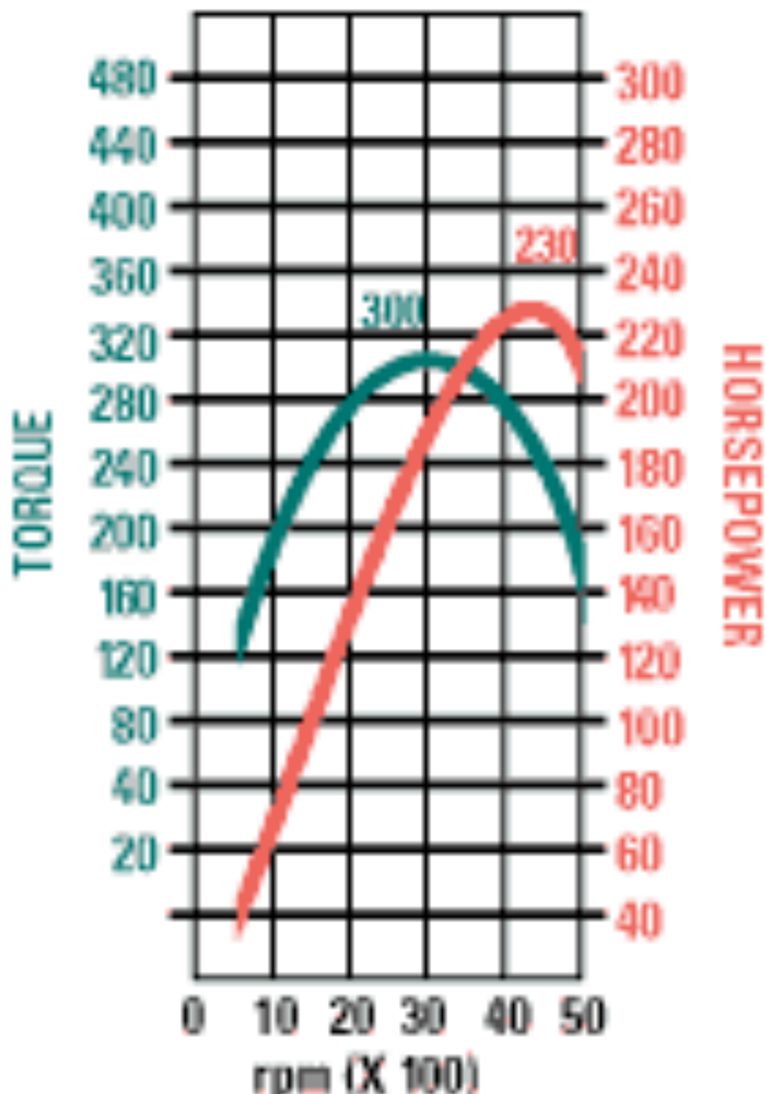
Otto engine, Dodge Ram pickup V8 5.9 L engine, 2004

Fundamental problem with ICEs:

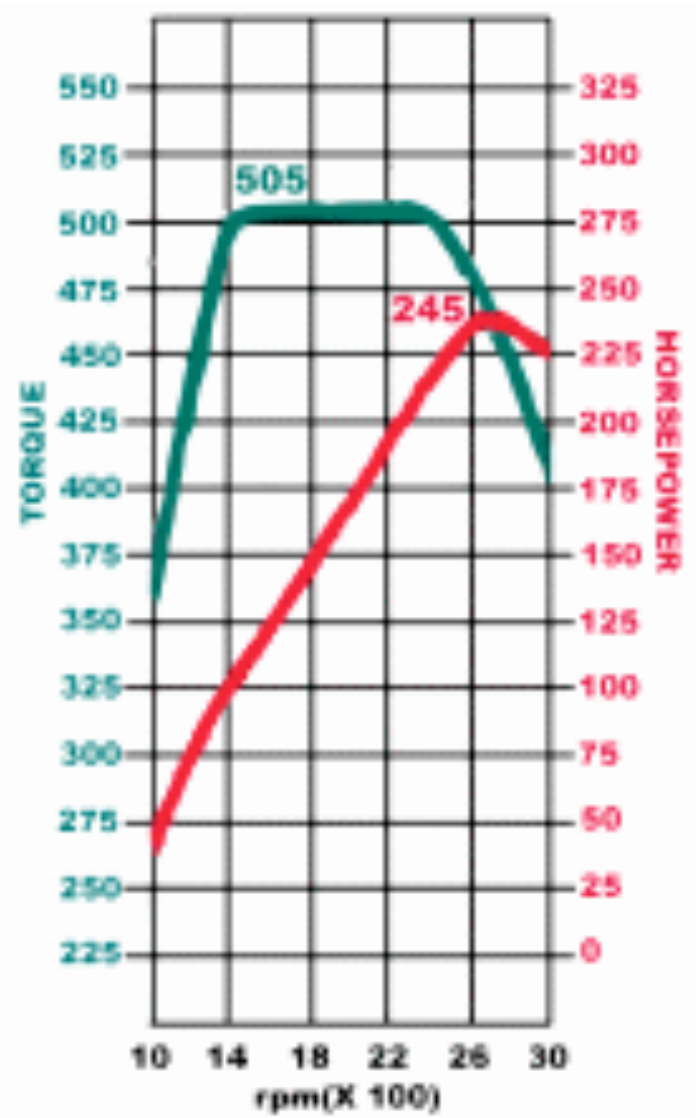
Low torque at low rpm. How do you start the car from a standstill? How do you accelerate?

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



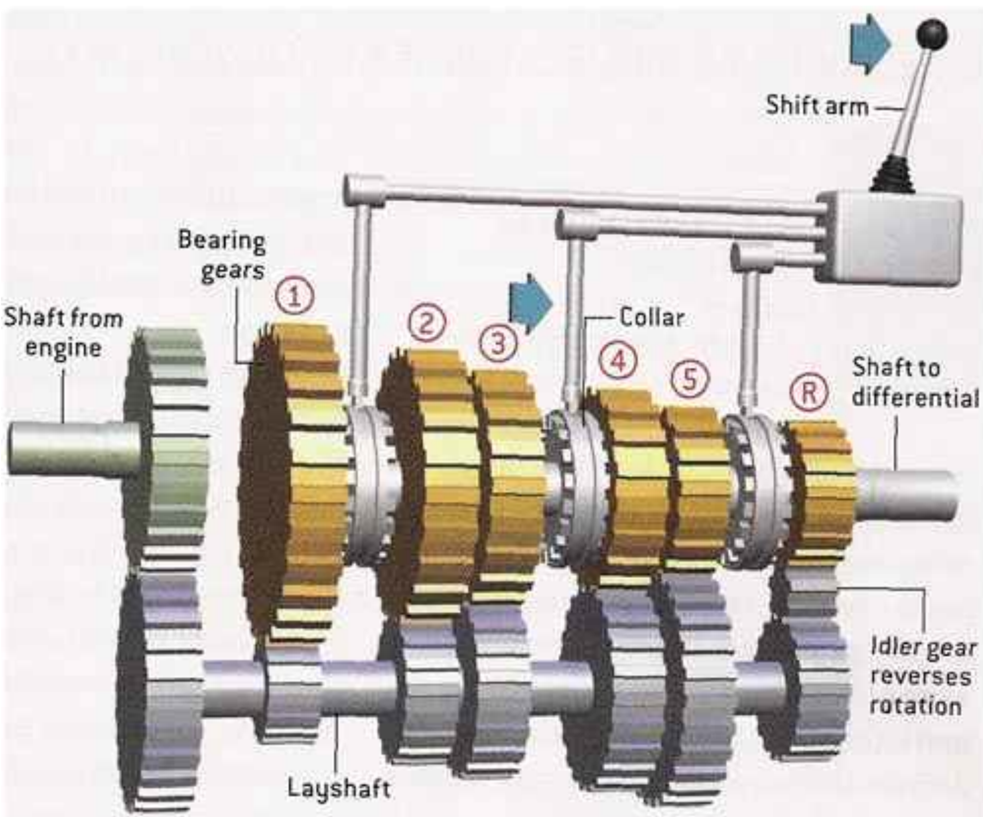
Diesel engine, Dodge Ram pickup 5.9 L, standard output, 2004
peak torque at 1400-2400 rpm

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

$P = \tau * \omega$. 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

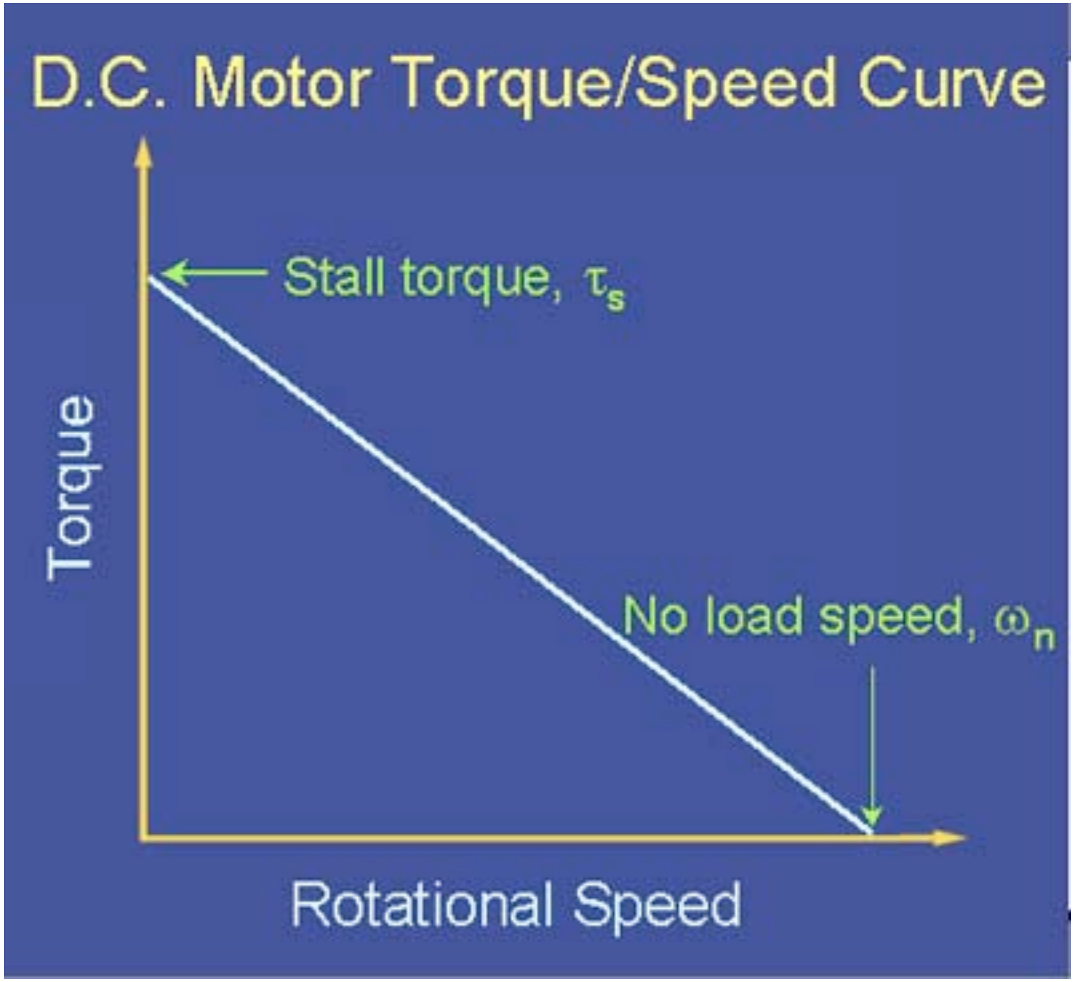


Manual transmission schematic, hyperlogos.org

Can we Achieve High Torque at Low Speeds?

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

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.

Electric motors driving wheels have single fixed gear

Figure: howstuffworks.com