GEOS 24705 / ENST 24705
The internal combustion engine and transportation

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

U.S. energy use, 2005

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

= 3 \times 10^{12} W / 300M people = 10,000 W/person

Projected Year 2005
From Year 2005
Efficiency Year 2005
Energy Distribution Year 2005
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/m³)
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*
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)
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)
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 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 patents spark-ignition 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, French engineer, designs and patents *(but doesn’t build)* the first 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.
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.”
“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 -> production in U.S.

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: Daimler & Maybach, having quit Otto’s company, invents prototype of modern engine fueled by liquid petroleum with carburetor.

1885: Karl Benz builds 3-wheeled automobile with flex-fueled engine.

1886-1889: Daimler/Maybach automobiles:
- 4 wheels, 4-cylinder engine, 10 mph top spd,
- first sale in 1892 (Benz has > 500 by 1899)

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
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later patents: spark ignition, sparkplug, carburetor, clutch, gear shift, radiator.

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Two-stroke engine
Simpler, cheaper

Advantages:

Higher power-to-mass since it is never left on—each stroke is a 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.
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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

Note means of converting linear motion to rotational
Four-stroke engine: Otto cycle
driver of most transportation

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

**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 the compression phase and yield balanced power.

Note central crankshaft allowing pistons to turn linear motion into rotational motion and to put work into the same shaft.
Four-stroke engines: generally have pairs of cylinders

Some high-power automobile engines have 8 cylinders, hence “V8”
Internal combustion engine history:
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 **biofueled 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*
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

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

BUT

- Heavier
- Slow to start

**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)
Why did the internal combustion engine win out?

In part, because fuel became cheap...

Figure from: Wikimedia Commons
Pitching small cars to the American people required new approaches....
Stagnation in fuel economy due to increased engine power

**Fuel Economy Trend, U.S. Cars, 1975-2011**

Plus Targets for 2021 and 2025

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

- Multiple competing technologies:
  - electric, gasoline, steam

- Hybrid gasoline-electric vehicles

- Multiple small car manufacturers

- Interest in fuel economy as response to fuel prices

- Fuel economy comparable to best small conventional cars today
  (though at the expense of power)
**Fuel usage in transportation: where does energy go?**

**Thermodynamic losses in engine** (typically Otto cycle in real engines gives ~ 75% loss to heat, only 25% becomes kinetic energy)

..and then what happens to the kinetic energy?  
*Must dissipate somehow…*

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 $v$

So less power is used to accelerate the air. Adjust formula by some fudge factor that describes how “streamlined” the car shape is:

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

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.

\[ F_{rr} \]

... and we’ll leave derivation of the power loss to rolling resistance to the problem set.