GEOS 24705 / ENST 24705 / ENSC 21100

Lecture 17
Transportation & engines
Cars: explosion of development after 1885 proof of concept

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

Merger to Daimler-Benz 1926
10 years later: demonstrations in the U.S.

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

1895: Chicago Times-Herald sponsors first automobile race, Hyde Park to Evanston and back: 60+ entrants, 11 start (6 at start line), 2 finishers

“A Prize for Motors,” with a $5,000 purse for “inventors who can construct practicable, self propelling road carriages.”

Duryea car beats imported Benz

10:23 to finish (5 mph)

2 electric cars did not finish
20 years later: Production improvements in U.S.

1896: Henry Ford starts company, Detroit

1908: Mass production of Ford Model Ts
first affordable automobile for the middle class
15,000 orders placed within days, > 15 M total sold
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:
Higher power-to-mass since it 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
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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 (same for 2-stroke)
Thermodynamic cycles: Otto cycle  *(Rochas 1862, Otto 1876)*

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

Ideal Otto efficiency = $1 - \left( \frac{1}{r} \right)^{\gamma + 1}$ where $r = \text{compression ratio } V_1/V_2$

($\gamma = \text{specific heat ratio, property of the gas, } \sim 1.4 \text{ for air}$)
**Efficiency is a function of compression ratio, so design for high ratios: \( r \sim 7-10 \) in cars**

**Ideal Otto efficiency**
(actual is \( \sim \frac{1}{2} \) as large)

\[
\text{ideal Otto efficiency} = 1 - \left( \frac{1}{r} \right)^{\gamma - 1}
\]

where \( r = \text{compression ratio } V_1/V_2 \)

\( \gamma = \text{specific heat ratio, property of the gas, } \sim 1.4 \text{ for air} \)
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)
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.
Thermodynamic cycles: **Otto cycle** *(Rochas 1862, Otto 1876)*

Do you need to combust at constant volume? Wastes power (area on graph)
Thermodynamic cycles: **Diesel cycle** *(Diesel 1893)*

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
  \[ r \sim 14 - 22 \text{ or more} \]

**ideal Diesel efficiency** = \[ 1 - \left( \frac{1}{r} \right)^{\gamma} \cdot \frac{(\alpha^\gamma - 1)}{(\gamma(\alpha - 1))} \]

*where \( \alpha \) 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)γ * (αγ -1)/(γ(α -1))]

where α is the “cutoff ratio” V₄/V₃. Lower than Otto for a given r, but r is bigger for Diesel.
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 \times \text{distance} \quad \text{units of energy}

Power = \text{energy/time} = \text{torque} \times \text{rotation rate} \ (P = \tau \times \omega)
NO internal combustion engines runs well at slow speeds

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)

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

\[ P = \tau \ast \omega. \] If want power \( P \), and \( \tau \) is constrained, must have high \( \omega \)
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**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

\[ P = \tau \times \omega. \] If want power \( P \), and \( \tau \) is constrained, must have high \( \omega \).
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.*
Overall: drawbacks of the ICE

- Engine speed mismatched to wheel speed
  \[\rightarrow \textit{requires transmission}\]

- Single power system
  \[\rightarrow \textit{requires drivetrain}\]

- Single power system but wheels must rotate at different rates (when going around curves)
  \[\rightarrow \textit{requires ‘differential’}\]
Which engine to choose?

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

1. **Power/mass:** heavier engines harder to move or carry.

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

3. **Torque:** “turning force”. Affects how fast you can accelerate, or how big a load you can get moving.
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)
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*
Individual motors weigh 6000 pounds and draw over 1000 amps.

Electric motors driving wheels have single fixed gear.

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
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


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...

1888: Bertha Benz’ drive
1908: Production of Model T Fords begins in Detroit
1973 oil shock
1973 Datsun 510

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

the era of diversity

The “Big 3” era
OPEC crisis drove interest in fuel economy
Pitching small cars to the American people required new approaches....

In your wallet, you'll know it's right.

If a car doesn't have to be an extension of your manhood.

Either you have it or you don't. No amount of bulging chrome, 5 or 6 on the floor, or overhead cams has ever turned a milkspoon into Attila the Hun.

The Renault 10 is for men who don't need a crutch. It is, simply and stubbornly, an intelligent well-made automobile.

It delivers a very efficient 35 miles a gallon. Does 0-60 in 15 seconds, and has a top speed of 85 mph. Enough for anybody who isn't trying to prove something. It's also got disc brakes on all four wheels to protect you from guys who are.

Besides, it even out-handles and out-turns a lot of fancy-price fantasy wagons.

Our price is a mere $1725. But for another 50 bucks you can get bucket seats that fold down into a bed.
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**

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:

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

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.
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.

\[ \text{Force of rolling friction} \text{ is proportional to normal force that opposes car's weight against ground.} \]

\( \text{Force of rolling friction} \propto \text{normal force} \)

\( F_{\text{Norm}} = m \, g \)

\( F_{\text{rr}} = C_{\text{rr}} \, m \, g \)

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

\[ P = C_{\text{rr}} \, m \, g \, v \]
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*

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

Sanding nozzle
*Image: HowStuffWorks*