The Automobile Industry

Environmental issues:

- During manufacturing
- During use
- During recycling/disposal
The basic issues

Automobiles
- are relatively massive → issue of quantity of materials
- have a complex design → issues of material variety
  → complex recycling
  → heavy metals, toxics, solvents used in manufacturing
- consume energy during their use → issue of efficiency (car weight, engine type)
- pollute during their use → issue of fuel type
  → issue of used oil disposal (minor issue)
- generate sizeable amounts of solid waste at the end of life
  → issue of recycling
  → issue of old tires (not recyclable)

Where is the greatest energy consumption? In manufacturing or in using the car?

A rough calculation:

Manufacturing:
Car weighs about 1400 kg
50 MJ needed per kg of material
\[
\frac{50 \text{ MJ}}{\text{kg}} \times \frac{1400 \text{ kg}}{\text{car}} = \frac{70,000 \text{ MJ}}{\text{car}} = \frac{70 \text{ GJ}}{\text{car}}
\]

Use:
150,000 miles during lifetime
25 miles per gallon
Gasoline generates 31 MJ/L = 117 MJ/gallon
\[
\frac{150,000 \text{ mi}}{\text{car}} \times \frac{\text{gal}}{25 \text{ mi}} = \frac{6,000 \text{ gallons}}{\text{car}}
\]
Gasoline generates 31 MJ/L = 117 MJ/gallon
\[
\frac{6,000 \text{ gallons}}{\text{car}} \times \frac{117 \text{ MJ}}{\text{gallon}} = \frac{702,000 \text{ MJ}}{\text{car}} = \frac{702 \text{ GJ}}{\text{car}}
\]
Levels at which effort are being concentrated:

1. Design for fuel efficiency:
   - streamlined aerodynamics (pretty much at its limit by now)
   - materials for lighter weight
   - hybrid engines; plug-in hybrids
   - electric cars

2. Design for cleaner fuels:
   - biodiesel, used vegetable oil
   - ethanol (from sugars, from cellulose)
   - fuel cells with hydrogen as a fuel

3. Design for better recycling:
   - materials reduction / substitution
   - labeling of plastics
   - use of recycled plastics
   - assembly for disassembly
   - development of recycling infrastructure
     (prompted by regulations)

4. Lean manufacturing:
   - avoidance of toxics, minimization of solvents, etc.
   - emphasis on quality
   - Toyota and Subaru at the lead

Stage 1:

AUTOMOBILE MANUFACTURING
Environmental impacts during manufacturing

A typical car contains about 15,000 parts, but the first few account for most of the weight of the vehicle (chassis, engine, body panels, etc.)

Not all parts are equally large and important.

Figure 2. Distribution of parts by weight.
Comparing the making and running of different cars:

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric car</td>
<td>1385</td>
<td>123.1</td>
<td>42.8</td>
<td>384 (70%)</td>
<td>1.5</td>
<td>0.01</td>
<td>551.4</td>
</tr>
<tr>
<td>PEM fuel cell with Hydrogen from windmill</td>
<td>800</td>
<td>178</td>
<td>~30</td>
<td>195 (48%)</td>
<td>1.5</td>
<td>---</td>
<td>404.5</td>
</tr>
<tr>
<td>Standard ICV</td>
<td>1395</td>
<td>80.8</td>
<td>15.5</td>
<td>788 (89%)</td>
<td>1.5</td>
<td>2.3</td>
<td>888.1</td>
</tr>
<tr>
<td>ICV with all steel replaced by wrought Al</td>
<td>1045</td>
<td>134.2</td>
<td>16.1</td>
<td>668</td>
<td>1.2</td>
<td>2.3</td>
<td>821.8</td>
</tr>
<tr>
<td>ICV with all steel replaced by 50% recycled Al</td>
<td>1045</td>
<td>96.8</td>
<td>15.7</td>
<td>668</td>
<td>1.2</td>
<td>2.3</td>
<td>784</td>
</tr>
<tr>
<td>ICV with all steel replaced by glass-FRP</td>
<td>1145</td>
<td>85.8</td>
<td>15.6</td>
<td>704</td>
<td>1.3</td>
<td>2.3</td>
<td>809</td>
</tr>
<tr>
<td>ICV with all steel Replaced by carbon-FRP</td>
<td>925</td>
<td>137.4</td>
<td>16.1</td>
<td>624</td>
<td>0.9</td>
<td>2.3</td>
<td>780.7</td>
</tr>
</tbody>
</table>

ICV = Internal Combustion Vehicle
PEM = Proton-Exchange Membrane (fuel cell)
FRP = Fiber-Reinforced Polymer
Lean Manufacturing of the Smart Car

The different parts of the production system “SMART-PLUS”

Manufacturing plant in Hambach, France:
- Green building
- Workers trained in separating wastes
- Environmentally conscious suppliers
- Just-in-time manufacturing
- Press-fit plastic panels
- Other DfRecycling measures
- Minimization of transport
- etc.

4.8 L/100km = 49 mpg

>10% in recycled content

Dilemma: Organic-solvent or water-based paints?

<table>
<thead>
<tr>
<th>Organic-solvent paint</th>
<th>Water-based paint</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well tested technology</td>
<td>Newer technology</td>
</tr>
<tr>
<td>Existing equipment</td>
<td>More difficult to achieve good surface finish</td>
</tr>
<tr>
<td>Lower energy use in drying</td>
<td>Higher energy use in drying</td>
</tr>
<tr>
<td>Air emissions:</td>
<td>No air emissions</td>
</tr>
<tr>
<td>- Workers exposure</td>
<td></td>
</tr>
<tr>
<td>- Air-emission treatment</td>
<td></td>
</tr>
</tbody>
</table>

Automotive painting: From a purchase to a service

Old way – purchase: Assembly plant purchases paints by the bucket from a paint supplier (chemical company). It is in the paint supplier’s interest to sell as much paint as possible. The more waste, the better from the paint supplier.

New way – service: Assembly plant hires people from the paint supplier to do the painting of its cars. The paint supplier is paid not by the amount of paint used but by the number of cars painted. It is now in the paint supplier’s interest to use the least paint possible, certainly to waste the least paint possible. Waste is reduced.
Stage 2:

AUTOMOBILE USAGE

Environmental impacts during use

Pollution caused by automobiles =

\[
\text{Pollution / unit of fuel} \times \text{Units of fuel / kilometers traveled} \times \text{Kilometers traveled / trip} \times \text{Number of trips / car} \times \text{Number of cars}
\]

(reduce by switching to an alternative fuel that pollutes less)

(reduce by increasing fuel efficiency or by decongesting traffic)

(promote mixed use of land to decrease distances between home, shops, schools and place of work, or move people from suburbs back to cities)

(incite people to drive less or promote public transportation)

(make it “hip” no longer to have a car – cultural change)

On which of those factors are engineers to work?
Why an electric motor?
Because the internal-combustion engine is so bad…

A Comparison of Two Engines

<table>
<thead>
<tr>
<th>Internal-combustion engine</th>
<th>Electric motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Only 35% efficient at best</td>
<td>80-90% efficient</td>
</tr>
<tr>
<td>(needs a radiator for cooling)</td>
<td>(no need for a radiator)</td>
</tr>
<tr>
<td>Air emissions</td>
<td>Zero direct emissions</td>
</tr>
<tr>
<td>Peaky torque-rpm curve</td>
<td>Broad torque-rpm curve</td>
</tr>
<tr>
<td>(needs a transmission)</td>
<td>(does not need a transmission)</td>
</tr>
<tr>
<td>Power loss in idle</td>
<td>No idle</td>
</tr>
<tr>
<td>Irreversible energy conversion</td>
<td>Regenerative braking</td>
</tr>
<tr>
<td>Big and heavy</td>
<td>Small and light</td>
</tr>
<tr>
<td>(250 hp in 600 lbs = 0.7 kW/kg)</td>
<td>(75 kW in 13 kg = 5.8 kW/kg)</td>
</tr>
<tr>
<td>Noisy</td>
<td>Quiet</td>
</tr>
</tbody>
</table>

So, why didn’t we have electric cars for decades?
Because we didn’t have good batteries to store enough electricity on board of the vehicle! And today’s batteries still come a bit short.
Ways to get electricity on board of a moving vehicle:

1. Batteries, but
   - they are heavy
   - slow to recharge
     (overnight at home instead of a few minutes at a pump)
   - cannot hold energy for more than 300 miles or so
   - contain special materials (lithium, nickel, cobalt)
   - are susceptible to catch on fire
   - only as environmentally clean as the electricity used for charge
     (possibility of upstream pollution)

2. Supercapacitors: - highly reversible and efficient
   - heavy

3. Fuel cell: - still only 40% efficient but shows much promise
   - still bulky, problems with variable loads, problems with freezing
   - problematic storage of hydrogen
     high-pressure gas?
     liquified?
     bound in metal hydride?

For reference, gasoline contains 13,000 Wh/kg
but the internal combustion engine is only 35% efficient

4.550 Wh delivered per kg of gasoline
HYBRIDS

Since 1997 in Japan.
Since 2000 in United States.
Now commonplace in the US.
Also popular in Europe.

Sales of light-duty hybrid vehicle in the US grows at about 35% each year.

Toyota remains the leading seller of hybrids in the US, led by the Prius.

Two types of hybrids

Parallel hybrid (on the market; ex. Toyota Prius)

Series hybrid
A plug-in hybrid (PHEV) is a hybrid car with larger batteries and an extension cord.

It can be filled up at the gas station or plugged in into a domestic 110-volt outlet. “It's like having a second fuel tank that you always use first – only you fill up at home, from a regular outlet”, at an equivalent cost of under $1/gallon.

From the opposite perspective, the car can also be seen as an electric vehicle with a gas-tank backup.

There is more:

- If driving is mostly local, filling with gas may become unnecessary.
- Lifetime service costs are lower for a vehicle that is mainly electric.
- A PHEV can provide power to an entire home in the case of an electrical outage.
- A fleet of PHEVs could power critical systems during emergencies.

What other alternatives do we have besides hybrids, plug-in hybrids, and fully electric cars?
4. Compressed air

In 1979, as America found itself embroiled in an energy crisis, Missouri-based engine designer Terry Miller built a car that ran on an abundant, zero-emission fuel source—air. Compressed-air engines had been used in some locomotives and trucks since the 1800s, but Miller streamlined the design for his Air Car One (top photo). Pressure generated by the release of compressed air from onboard tanks drove the car’s engine. Miller’s vehicle was never commercially produced, but interest remains. India’s Tata Motors, for one, has developed a compressed-air car prototype (bottom photo).

5. Electric car

Automakers have produced electric cars off and on for over a century. Ohio-based Baker Motor Vehicle Co. was among the most successful, selling thousands of its electrics to wealthy consumers (including Thomas Edison) from 1899 to 1915. But while each Baker (1916 model in photo) ran on no fewer than 12 cell batteries, its top speed was just 14 miles per hour. In contrast, many less expensive, gas-powered cars could exceed 40 mph. Today, as gas prices soar and battery technology improves, all-electric cars might well make a comeback.
6. Gas-electric hybrid

In 1901, Czech engineer Ferdinand Porsche unveiled the Mixte (photo). French for “mixed,” the car was a forerunner to today’s gas-electric hybrids, which use less gasoline and create fewer emissions than conventional gas-powered cars. But unlike Porsche’s later sports cars, the Mixte was too far ahead of its time. The four-seater model required nearly two tons of batteries, which made it too expensive to be produced in bulk. (The model in the photo is a two-seater.) Improved battery technologies have helped reduce costs and allow modern hybrids like Toyota’s Prius to sell increasingly well.

7. Solar electric

In 1987, General Motors harnessed solar to help run its Sunraycer experimental racing vehicle (above). The Sunraycer’s photovoltaic cells converted the sun’s energy directly into electrical energy; the electricity then powered an electric motor that drove the car. Although similar technology is still used in special aerodynamic racecars, any purely solar-powered road vehicle designed to meet general safety standards would be larger and much heavier than the Sunraycer, requiring more power than can yet be generated to achieve highway speeds.
8. Biofuels

Henry Ford (photo, at the wheel of a Model T) designed his "Tin Lizzie" to run on either gasoline or a hemp-based fuel. But with the discovery of large crude-oil deposits in the early 20th century, oil prices dropped and gasoline derived from the oil became Ford's and other carmakers' fuel of choice. Unlike fossil fuels, biofuels come from renewable resources, typically plants. Although biofuels have many advocates, skeptics point out that they currently require too many resources to be used on a widespread commercial basis.

9. Hydrogen fuel cells

Fuel cells combine fuel (usually hydrogen) and oxygen to produce electricity through chemical reactions similar to those that occur in batteries. While some automakers are now trying to develop hydrogen fuel-cell cars, General Motors actually designed its own, the Electrovan, as early as 1966. While the Electrovan (photo) could travel up to 70 mph and 120 miles between refuelings, it was too expensive to produce commercially.

Recent advances have made affordable fuel cells more likely, and in 2003 the U.S. Congress pledged $1.2 billion to make such vehicles cost-effective by 2020.
Examples of fuel-cell vehicle prototypes

Graph generated from elements gathered from Prof. Lee R. Lynd to whom credit is due
Alternatives for energy source and drivetrains, ranked according to greenhouse gas emissions

<table>
<thead>
<tr>
<th>Primary energy source – Onboard energy storage – engine type</th>
<th>Emissions (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Solar – Electricity – Electric motor</td>
<td>1.2%</td>
</tr>
<tr>
<td>2. Wood – Ethanol – Internal combustion engine</td>
<td>2.2%</td>
</tr>
<tr>
<td>3. Solar – Hydrogen – Fuel cell</td>
<td>2.4%</td>
</tr>
<tr>
<td>4. Solar – Hydrogen – Internal combustion engine</td>
<td>6.5%</td>
</tr>
<tr>
<td>5. Nuclear – Battery – Electric motor</td>
<td>6.6%</td>
</tr>
<tr>
<td>6. Nuclear – Metal hydrides – Fuel cell</td>
<td>14.9%</td>
</tr>
<tr>
<td>7. Wood – Methanol – Fuel cell</td>
<td>15.1%</td>
</tr>
<tr>
<td>8. Wood – Methanol – Internal combustion engine</td>
<td>24.9%</td>
</tr>
<tr>
<td>9. Wood – “Natural” gas – Internal combustion engine</td>
<td>26.5%</td>
</tr>
<tr>
<td>10. Nuclear – Metal hydrides – Internal combustion engine</td>
<td>32.7%</td>
</tr>
<tr>
<td>11. Natural gas – Methanol – Fuel cell</td>
<td>56.2%</td>
</tr>
<tr>
<td>12. Natural gas – Battery – Electric motor</td>
<td>65.8%</td>
</tr>
<tr>
<td>13. Natural gas or oil – Liquid propane gas (LPG) – Internal combustion engine</td>
<td>74.0%</td>
</tr>
<tr>
<td>14. Natural gas – Natural gas – Internal combustion engine</td>
<td>76.2%</td>
</tr>
<tr>
<td>15. Nuclear – Liquid hydrogen – Internal combustion engine</td>
<td>82.4%</td>
</tr>
<tr>
<td>16. Oil – Diesel – Internal combustion engine</td>
<td>84.5%</td>
</tr>
<tr>
<td>17. Natural gas – Methanol – Internal combustion engine</td>
<td>95.0%</td>
</tr>
<tr>
<td>18. Marginal electric power – Battery – Electric motor</td>
<td>98.2%</td>
</tr>
<tr>
<td>19. Oil – Standard gasoline – Internal combustion engine</td>
<td>98.9%</td>
</tr>
<tr>
<td>20. Oil – Reformulated gasoline – Internal combustion engine</td>
<td>100%</td>
</tr>
<tr>
<td>21. Coal – Methanol – Fuel cell</td>
<td>102.2%</td>
</tr>
<tr>
<td>22. Coal – Battery – Electric motor</td>
<td>108.7%</td>
</tr>
<tr>
<td>23. Corn + coal – Ethanol – Internal combustion engine</td>
<td>112.4%</td>
</tr>
<tr>
<td>24. Coal – Methanol – Internal combustion engine</td>
<td>166.8%</td>
</tr>
</tbody>
</table>

Percentages are in comparison with the base-case emissions.

Source:

Figure 3. Greenhouse gas emission reduction in relation to required infrastructural change/development.

Emission reductions = 100 - values from Table 1. The abscissa scale is the average from Table 4. Identification numbers are as for Table 4.
... but, wait a minute:

1. The fuel cell car does not have an internal combustion engine at all and therefore needs no transmission. This reduces the drive train loss from 31% to 10%.

2. Projections are to put hydrogen on board (instead of methanol + reformer).

This changes the picture significantly:
Stage 3:

AUTOMOBILE RECYCLING

![Automobile Recycling Image](image-url)
Issues faced in automotive recycling

- Economics:
  Low-value parts and materials make it difficult to run a profitable business.
  Prices on the recycling markets fluctuate greatly.
  Auto Shredder residue (ASR) has to be landfilled at a cost.

- Sorting of plastics:
  Plastics recycling requires sorting, and a large variety of similar looking plastics creates complications.
  Labeling of plastics has helped greatly, but it is still absent in older models.

- Environmental regulations:
  Contamination by spilled fluids and handling of hazardous materials have been the object of strict regulations.
  Incineration and landfilling of ASR is subject to regulations as well.
SORTED PLASTICS – Researchers built a series of tanks to separate recycled plastics by type using Argonne’s froth flotation process. The polyolefin flows down by chemist Joe Pomykala while chemical engineer Jeff Spangenberger works at the next separation station.

RECYCLED AUTO PLASTICS – Project Manager Sam Jody holds a knee bolster for a car processed from recovered polyolefin. Automotive plastic recycling begins with auto shredder residue (left), is separated into specific plastics (right) – in this case polyolefins – and made into plastic parts for new cars.
Recycled plastics in the BMW 3-series

Tires: A real problem at end of life

A few statistics:

About 300 million tires sold in US annually
More than 4 million tons per year
Equivalent to about 1 tire per person per year
Discarded tires: 80% passenger cars
20% trucks, buses

“Recycling”: 15%
Use in highways: 31%
Burning as tire-derived fuel: 51%
Incinerated or landfilled: 2%

New tires: no more than 2% “recycled” rubber
Retreads: up to 75% reused content

Tire “recycling” is really cascading: use in playground, artificial reefs, floor mats, dock bumpers, carpet padding, tracks and athletic surfaces.