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
\[
\frac{150,000 \text{ mi}}{\text{car}} \times \frac{\text{gal}}{25 \text{ mi}} = \frac{6,000 \text{ gallons}}{\text{car}}
\]
\[
\frac{6,000 \text{ gallons}}{\text{car}} \times \frac{117 \text{ MJ}}{\text{gallon}} = \frac{702,000 \text{ MJ}}{\text{car}} = \frac{702 \text{ GJ}}{\text{car}}
\]
Adding a few extra considerations, such as fuel processing and insurance:

Lion’s share of energy consumed during use

Energy consumed over the lifetime of a typical car. The total amount of energy represented by the pie is 1.2 million MJ.

Lion’s share of toxics release during manufacture

Toxic releases over the lifetime of a typical car. The total releases represented by the pie are 66.3 kg.


Energy versus Cost

![Energy versus Cost chart]

Environmental Impact

Customer’s Basis for Decision

Lack of alignment!
In applying Design for Environment (DfE) to the automobile, keep in mind the time horizon.

According to BMW:

• It takes 3 to 4 years to design a new model.
• More or less same model is manufactured during 7 to 8 years.
• Once on the road, the car is driven for about 10 to 12 years.

TOTAL length of time impacted by early design decisions:

20 to 24 years!

(Point of reference: 25 years = 1 generation.)

Possible levels of automotive redesign

From tinkering at the margin to the social revolution!

1. Re-design of parts: Aluminum or plastic radiator cap
   Longer-lasting tires and batteries
   Aluminum or steel engines

2. Re-design of assembly: Eco-friendly painting
   Facilitating disassembly
   Recycling of plastics

3. Re-design of automobile itself: Alternative fuels (ex. ethanol, methanol)
   Alternative powertrains (hybrids, fuel cells)

4. Re-design of transportation systems: Smart highways
   Public transportation

5. Re-thinking the need for mobility: Virtual office (telecommuting)
   Community layout
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 car

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 or 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 at the lead, Daimler-Benz close behind

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.

![Distribution of parts by weight](image2/explodedcarparts.png)
Average material distribution of automobiles in 1998
(http://1877endoflifevehicles.com/rematerials.cfm)
Steel on a per-car basis
(1995 numbers)

New steel: 811.6 kg
Recycled steel: 109.3 kg
= 920.9 kg of input

70.1 kg losses in processing steel
850.8 kg into making parts
67.6 kg losses during manufacturing
783.2 kg into new car
76.7 kg losses during use & abandoned cars
706.5 kg of hulk going to dismantler
25.9 kg losses in dismantling/recycling
680.60 kg recycled

109.3 kg to auto industry
571.3 kg to other industries

Plastics on a per-car basis
(1995 numbers)

Virgin polymers: 117.8 kg
Recycled plastics: 2.5 kg
= 120.3 kg of input

3.3 kg losses in processing steel
117.0 kg into making parts
5.0 kg losses during manufacturing
112.0 kg into new car
7.5 kg losses during use & abandoned cars
104.5 kg of hulk going to dismantler/recycler
102 kg waste
2.5 kg recycled

571.3 kg to other industries
Much better numbers now from the CES database!

More accurate estimates of energy to make and use mid-sized cars:

<table>
<thead>
<tr>
<th>Material</th>
<th>Manufacturing (GJ/car)</th>
<th>Use (GJ/car)</th>
<th>Total (GJ/car)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional car</td>
<td>104</td>
<td>867</td>
<td>971</td>
</tr>
<tr>
<td>Lightweight car</td>
<td>107</td>
<td>759</td>
<td>866</td>
</tr>
<tr>
<td>Conventional car</td>
<td>79</td>
<td>867</td>
<td>946</td>
</tr>
<tr>
<td>with 90% recycled metals</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lightweight car</td>
<td>66</td>
<td>759</td>
<td>825</td>
</tr>
<tr>
<td>with 90% recycled metals</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(Source: Automotive Engineering, June 1997, page 80)

Clearly, making a lighter car gives a better environmental return than recycling materials.
Comparing the making and running of different cars:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric car (standard batteries)</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

VERY LIMITED SLACK: Toyota Motor Company
The Toyota Production System was created by Taiichi Ohno, the chief engineer of Toyota Motor Company in the years following the second world war. Ohno based his "lean production" system on the elimination of all wasted time and rework from the mass production system of the American auto manufacturers. Toyota's Takaoka Assembly Plant produces cars with a gross assembly time of under 18 hours, and with only 45 assembly defects per 100 cars. As a result of this efficient production system, Toyota is able to produce high quality automobiles as one of the industries lowest cost producers. Toyota Motor Corporation is an example of a company with very limited slack evidenced by there being little or no waste and inefficiency.

SOME SLACK: General Motors Corp.
GM's production system requires more than twice as many assembly hours to build a car as Toyota does. (40.7 hours at G.M.'s Framingham Assembly Plant vs. 18.0 hours at Toyota's Takaoka plant.) Furthermore, GM workers rack up three times as many defects as the Toyota workers (130 defects per 100 autos vs. 45 at Toyota). General Motors is an example of a company which has some slack which could be eliminated.

LOTS OF SLACK: Morgan Motor Company
Morgan Motor Company is proud to be the producer of the last coachbuilt car in the world. The Morgan factory is an anachronism in today's auto world. These true sports cars are built one at a time...by hand...just as they were when the factory was established in 1919. Skilled panel beaters form steel body panels over a frame made of wood. The company proudly advertises "There is no moving assembly line where tasks have been reduced to a monotonous routine." The staff numbers 130. Morgans are cult cars. The Morgan Plus Eight is one of the fastest accelerating cars in the world, capable of 0 to 60 in under 6 seconds. Demand for Morgans outstrips the company's production capability of 500 cars per year. As a result there is a 4 to 5 year waiting list for one of these fine automobiles. Morgan Motor Company is an example of a company which has survived in spite of a production process which has lots of slack. Compared to modern auto manufacturing plants, the Morgan plant embodies lots of waste and inefficiency. Even so, the high demand for the product relative to the production allows Morgan Motor Company to charge a premium price and stay in business.
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.

Fig. 4. The micro compact car AG from Daimler-Benz (Ref: http://www.daimler-benz.com).

(Planning for an Environment-Friendly Car, by Udo Mildenberger and Anshuman Khiare, Technovation, Vol. 20, 2000, pages 205-214.)

Biggest environmental issues in automotive manufacturing is PAINTING.

Largest fraction of environmental expenditure at an automobile assembly plant.

- High capital costs for air emission and waste treatment equipment
- High operating costs due to high energy and material use
- High operating cost due to waste treatment and disposal.

- **Air emissions** – Paint processes are subject to local authority regulation and visits from the authorities to ensure compliance. VOC emissions are the main concern, due to their potential to cause respiratory problems particularly for workers and local communities. European VOC Directives lowers emissions limits requiring either more capital equipment for abatement or alternative low solvent paints such as high solids, water-based paints or powder coats.

- **Solid Waste** – The primary source of hazardous waste from automotive plants is from painting, mostly from cleaning processes in the paint department. Solvents and heavy metals left in residues force the waste to be classified as hazardous. Although much material is recovered, this waste is typically around 25% of a plant’s total hazardous waste by weight.

- **Energy** – Curing ovens use vast amounts of energy for the paint to dry in an acceptable time. The shorter the curing time, the higher the energy use. This is further exacerbated by water-based paint requiring more time in curing ovens than solvent-based paint. Powder coats also require more use of ovens because of the thicker coats.
### Dilemma: Organic-solvent or water-based paints?

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

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**Stage 2:**

**AUTOMOBILE USAGE**
Environmental impacts during use

Pollution caused by automobiles

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

(1) (reduce by switching to an alternative fuel that pollutes less)
(2) (reduce by increasing fuel efficiency or by decongesting traffic)
(3) (promote mixed use of land to decrease distances between home, shops, schools and place of work, or move people from suburbs back to cities)
(4) (incite people to drive less or promote public transportation)
(5) (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...

No idling

Direct drive – No driveline losses

1.04% body skin
1.04% underfloor & wheel wells
0.52% throughflow

Direct drive –

More efficient – This number is smaller

100%
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 (needs a radiator for cooling)</td>
<td>80-90% efficient (no need for a radiator)</td>
</tr>
<tr>
<td>Air emissions</td>
<td>Zero direct emissions</td>
</tr>
<tr>
<td>Peaky torque-rpm curve (needs a transmission)</td>
<td>Broad torque-rpm curve (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 don’t we have electric motors in our automobiles today?

Because we do not have good enough batteries to store the electricity on board of the vehicle!

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)
   - too slow to charge to permit appreciable regenerative braking
   - cannot hold energy for more than 100 or so miles
   - contain hazardous materials (lead, metal hydrides, flammable or explosive compounds)
   - only as environmentally clean as the electricity at home ("elsewhere pollution"?)

2. Alternator:
   - reversible (doubles with the electric motor)
   - highly efficient (85 to 90%)
   - light weight
   - but mechanical energy needs to come from somewhere conventional internal-combustion engine? flywheel? supercapacitor?

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

And, there is the question:

How clean batteries really are?

Need to consider their life cycle...

Selected inventory data for the NiCd battery life cycle (excluding user phase) for different end-of-life treatment methods.

<table>
<thead>
<tr>
<th></th>
<th>Landfill, 100%</th>
<th>Incineration 69%</th>
<th>Recycling 90%</th>
<th>Recycling 100%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Landfill, 49%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Renewable energy (MJ/Wh)</td>
<td>0.16</td>
<td>0.16</td>
<td>0.14</td>
<td>0.14</td>
</tr>
<tr>
<td>Non-renew. energy (MJ/Wh)</td>
<td>5.18</td>
<td>5.15</td>
<td>4.29</td>
<td>4.32</td>
</tr>
<tr>
<td>CO₂ (g/Wh)</td>
<td>0.41</td>
<td>0.41</td>
<td>0.26</td>
<td>0.26</td>
</tr>
<tr>
<td>NOₓ (g/Wh)</td>
<td>0.56</td>
<td>0.56</td>
<td>0.34</td>
<td>0.47</td>
</tr>
<tr>
<td>SO₂ (g/Wh)</td>
<td>5.45</td>
<td>5.45</td>
<td>0.83</td>
<td>0.32</td>
</tr>
<tr>
<td>Cd (resource) (g/Wh)</td>
<td>4.3</td>
<td>4.1</td>
<td>0.41</td>
<td>0</td>
</tr>
<tr>
<td>Ni (resource) (g/Wh)</td>
<td>5.1</td>
<td>5.1</td>
<td>0.51</td>
<td>0</td>
</tr>
</tbody>
</table>

Source: Paper I
HYBRIDS

Since 1997 in Japan.
Since 2000 in United States.
They have become commonplace in the US.

Hardly seen in Europe.

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

In March 2012 alone, 48,206 were purchased in the US.

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
Modes of functioning of a parallel hybrid system

starting

cruising

up-hill driving

braking

Plug-in hybrids

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 and plug-in hybrids?

A car riding on biomass?
Here, view NOVA documentary with the Car-Talk guys:

http://www.pbs.org/wgbh/nova/car/program.html

<table>
<thead>
<tr>
<th>Alternatives for energy source and drivetrains, ranked according to greenhouse gas emissions</th>
<th>Primary energy source – Onboard energy storage – engine type</th>
<th>Percentages are in comparison with the base-case emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Solar – Electricity – Electric motor</td>
<td>1.2%</td>
</tr>
<tr>
<td>2</td>
<td>Wood – Ethanol – Internal combustion engine</td>
<td>2.2%</td>
</tr>
<tr>
<td>3</td>
<td>Solar – Hydrogen – Fuel cell</td>
<td>2.4%</td>
</tr>
<tr>
<td>4</td>
<td>Solar – Hydrogen – Internal combustion engine</td>
<td>6.5%</td>
</tr>
<tr>
<td>5</td>
<td>Nuclear – Battery – Electric motor</td>
<td>6.6%</td>
</tr>
<tr>
<td>6</td>
<td>Nuclear – Metal hydrides – Fuel cell</td>
<td>14.9%</td>
</tr>
<tr>
<td>7</td>
<td>Wood – Methanol – Fuel cell</td>
<td>15.1%</td>
</tr>
<tr>
<td>8</td>
<td>Wood – Methanol – Internal combustion engine</td>
<td>24.9%</td>
</tr>
<tr>
<td>9</td>
<td>Wood – “Natural” gas – Internal combustion engine</td>
<td>28.5%</td>
</tr>
<tr>
<td>10</td>
<td>Nuclear – Metal hydrides – Internal combustion engine</td>
<td>32.7%</td>
</tr>
<tr>
<td>11</td>
<td>Natural gas – Methanol – Fuel cell</td>
<td>56.2%</td>
</tr>
<tr>
<td>12</td>
<td>Natural gas – Battery – Electric motor</td>
<td>65.8%</td>
</tr>
<tr>
<td>13</td>
<td>Natural gas or oil – Liquid propane gas (LPG) – Internal combustion engine</td>
<td>74.0%</td>
</tr>
<tr>
<td>14</td>
<td>Natural gas – Natural gas – Internal combustion engine</td>
<td>78.2%</td>
</tr>
<tr>
<td>15</td>
<td>Nuclear – Liquid hydrogen – Internal combustion engine</td>
<td>82.4%</td>
</tr>
<tr>
<td>16</td>
<td>Oil – Diesel – Internal combustion engine</td>
<td>84.5%</td>
</tr>
<tr>
<td>17</td>
<td>Natural gas – Methanol – Internal combustion engine</td>
<td>95.0%</td>
</tr>
<tr>
<td>18</td>
<td>Marginal electric power – Battery – Electric motor</td>
<td>98.2%</td>
</tr>
<tr>
<td>19</td>
<td>Oil – Standard gasoline – Internal combustion engine</td>
<td>98.9%</td>
</tr>
<tr>
<td>20</td>
<td>Oil – Reformulated gasoline – Internal combustion engine</td>
<td>100%</td>
</tr>
<tr>
<td>21</td>
<td>Coal – Methanol – Fuel cell</td>
<td>102.2%</td>
</tr>
<tr>
<td>22</td>
<td>Coal – Battery – Electric motor</td>
<td>106.7%</td>
</tr>
<tr>
<td>23</td>
<td>Corn + coal – Ethanol – Internal combustion engine</td>
<td>112.4%</td>
</tr>
<tr>
<td>24</td>
<td>Coal – Methanol – Internal combustion engine</td>
<td>166.8%</td>
</tr>
</tbody>
</table>

Table 4. Required Infrastructural Changes/Development for Alternative Fuel Utilization

<table>
<thead>
<tr>
<th>Method</th>
<th>Off-Vehicle</th>
<th>On-Vehicle</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Production</td>
<td>Conversion</td>
<td>Delivery</td>
</tr>
<tr>
<td>Battery/Solar/Electric</td>
<td>3.2</td>
<td>3</td>
<td>1.3</td>
</tr>
<tr>
<td>Ethanol/Wood/Str. Comb</td>
<td>2.6</td>
<td>2.9</td>
<td>1.2</td>
</tr>
<tr>
<td>Hydrol/Elect. Comb</td>
<td>3.3</td>
<td>3.2</td>
<td>3.1</td>
</tr>
<tr>
<td>Hybrid/Elect. Comb</td>
<td>1.9</td>
<td>1.8</td>
<td>1.1</td>
</tr>
<tr>
<td>Hybrid/Elect. Comb</td>
<td>3.3</td>
<td>3.2</td>
<td>3.1</td>
</tr>
<tr>
<td>Hydrocarb/Natural Gas</td>
<td>2.4</td>
<td>2.9</td>
<td>3.1</td>
</tr>
<tr>
<td>Methanol/Wood/Str. Comb</td>
<td>2.8</td>
<td>3.3</td>
<td>1.6</td>
</tr>
<tr>
<td>Methanol/Elect. Comb</td>
<td>2.9</td>
<td>3.3</td>
<td>1.6</td>
</tr>
<tr>
<td>Methanol/Natural Gas</td>
<td>2.6</td>
<td>3.1</td>
<td>1.9</td>
</tr>
<tr>
<td>Methanol/Natural Gas</td>
<td>2.4</td>
<td>2.9</td>
<td>3.1</td>
</tr>
<tr>
<td>Methanol/Natural Gas</td>
<td>1.1</td>
<td>1.5</td>
<td>1.6</td>
</tr>
<tr>
<td>Battery/Elect. Comb</td>
<td>1.1</td>
<td>0.8</td>
<td>1.1</td>
</tr>
<tr>
<td>Li-Ion/Elect. Comb</td>
<td>1.1</td>
<td>1.1</td>
<td>1.6</td>
</tr>
<tr>
<td>Mg/Al. Comb</td>
<td>0.7</td>
<td>0.7</td>
<td>0.8</td>
</tr>
<tr>
<td>Li-Fly/Na/Sodium/Comb</td>
<td>2.4</td>
<td>2.4</td>
<td>2.9</td>
</tr>
<tr>
<td>Na/Cd/Sodium/Comb</td>
<td>0.7</td>
<td>0.4</td>
<td>0.9</td>
</tr>
<tr>
<td>Methanol/Natural Gas</td>
<td>0.7</td>
<td>1.2</td>
<td>1.6</td>
</tr>
<tr>
<td>Battery/Mg Pow/Elect.</td>
<td>0.9</td>
<td>0.7</td>
<td>1.1</td>
</tr>
<tr>
<td>Sodium/Ca/Str. Comb</td>
<td>0.1</td>
<td>0.5</td>
<td>0.9</td>
</tr>
<tr>
<td>PFG/Str. Comb</td>
<td>0.1</td>
<td>1.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Methanol/Coal/Elect.</td>
<td>0.6</td>
<td>2.7</td>
<td>1.6</td>
</tr>
<tr>
<td>Battery/Coal/Elect.</td>
<td>0.6</td>
<td>0.3</td>
<td>1.1</td>
</tr>
<tr>
<td>Methanol/Coal/Str. Comb</td>
<td>1.1</td>
<td>1.6</td>
<td>1.6</td>
</tr>
<tr>
<td>Methanol/Coal/Elect.</td>
<td>0.6</td>
<td>2.1</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Ratings for infrastructural change/development:
1. No change
2. Minor quality modification to existing infrastructure, no major expansion
3. Significant modification to existing infrastructure
4. Substantially new technology, major development work required
5. Substantially new technology, major development work required, major constraint to implementing alternative

Results reflect ratings from eight completed surveys received out of eleven sent out.

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.
Could ethanol vehicles pose a significant risk to health?

Although it is widely touted as an eco-friendly, clean-burning fuel, ethanol carries health hazards, according to a 2007 study by Stanford University atmospheric scientist Mark Z. Jacobson. If every vehicle in the United States ran on fuel made primarily from ethanol instead of pure gasoline, respiratory-related deaths and hospitalizations likely would increase, he claims.

"We found that E85 vehicles reduce atmospheric levels of two carcinogens, benzene and butadiene, but increase two others—formaldehyde and acetaldehyde," Jacobson said. "As a result, cancer rates for E85 are likely to be similar to those for gasoline. However, in some parts of the country, E85 significantly increased ozone, a prime ingredient of smog."

Making it into mainstream media

... and there even existed for a brief time a fuel-cell motorcycle!

This used to be posted at http://www.envbike.com but seems to have disappeared.
The bike probably never went past the prototype stage.

This motorcycle was not just quiet, it was silent!
The complete fuel-cell system is more than the cell stack...
The Hy-Wire concept by General Motors, also nicknamed the “skateboard” is a thin platform containing all the driving elements: wheels and steering (1), fuel cell array (2), hydrogen tanks (5), electric motor (9), etc.

The body is a light shell that can be easily placed on the platform and changed to meet the desires of the driver.

http://www.pbs.org/wgbh/nova/sciencenow/3210/01-car-nf.html
The fuel-cell energy source could be hydrogen, methanol, or gasoline.

Figure 2. Summary of monetised life-cycle impacts
(Source: Bent Sørensen, Total life-cycle assessment of a PEM fuel cell car, 2006)
Study comparing efficiencies if source of energy is oil

ICE, Internal Combustion Engine

HICE, Parallel Hybrid

AFC, Fuel Cell

… 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:

Paths to get there:

- Internal combustion engine (ICE) electric hybrid
  - Fossil
  - Hydrogen

- (ICE) mechanical drivetrain
  - Fossil fuels
  - Here now

- Development of hybrid vehicle systems
  - Electric drives
  - Controls
  - Energy storage

- Development of fuel cell power systems at entry level cost and power density

- Hybrid
  - Directive drive

- Fuel cell electric hybrid
  - Fossil
  - Renewable liquid
  - Hydrogen

- Fuel cell electric direct drive
  - Want to be here

The evolution of vehicle propulsion systems from gasoline-powered to fuel cell-powered.


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**FUEL EFFICIENCY BY TYPE**

<table>
<thead>
<tr>
<th>TECHNOLOGY</th>
<th>SOURCE FUEL</th>
<th>WELL-TO-STATION EFFICIENCY</th>
<th>VEHICLE MILEAGE</th>
<th>VEHICLE EFFICIENCY</th>
<th>WELL-TO-WHEEL EFFICIENCY</th>
</tr>
</thead>
<tbody>
<tr>
<td>TESLA ELECTRIC</td>
<td>NATURAL GAS</td>
<td>62.8%</td>
<td>110 Wh/km</td>
<td>3.18 kph</td>
<td>1.14 km/MJ</td>
</tr>
<tr>
<td>HYBRID (gas/electric)</td>
<td>CRUDE OIL</td>
<td>81.7%</td>
<td>55 mpg</td>
<td>0.68 kph</td>
<td>0.556 km/MJ</td>
</tr>
<tr>
<td>COMMUTER CAR (gas)</td>
<td>CRUDE OIL</td>
<td>81.7%</td>
<td>53 mpg</td>
<td>0.63 kph</td>
<td>0.478 km/MJ</td>
</tr>
<tr>
<td>SPORTS CAR (gas)</td>
<td>CRUDE OIL</td>
<td>81.7%</td>
<td>20 mpg</td>
<td>0.24 kph</td>
<td>0.202 km/MJ</td>
</tr>
<tr>
<td>HYDROGEN FUEL CELL</td>
<td>NATURAL H2</td>
<td>52.5%</td>
<td>64 kwh</td>
<td>0.37 kph</td>
<td>0.348 km/MJ</td>
</tr>
</tbody>
</table>

Source: http://www.teslamotors.com/goelectric/efficiency
The Tesla electric car

- 160, 230, or 300 mile range battery pack
- 45 minute "QuickCharge"
- > $100,000 price tag

The top three international car companies are getting prepared for electric cars.

<table>
<thead>
<tr>
<th>General Motors</th>
<th>Toyota</th>
<th>Volkswagen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chevy Volt</td>
<td>e-RAV4</td>
<td>e-Bugatti</td>
</tr>
</tbody>
</table>

News item:
December 01, 2011
GM offers to buy back Chevrolet Volts from fearful owners

News item:
Tesla Falls as Toyota Prices Electric RAV4 Near $50,000
By Alan Ohnsman - May 8, 2012 – Bloomberg Report
Stage 3:

AUTOMOBILE RECYCLING

The basics of recycling automobiles

Old cars are typically hauled to an automobile dismantler, where reusable parts are removed. After removing the reusable parts and other items like batteries, tires and fluids, the hulks are usually shipped to ferrous scrap processors where they are weighed for payment and unloaded.

At a scrap yard, hulks go into the shredder. The shredding process, which handles one car every 45 seconds, generates three streams: iron and steel; nonferrous metal; and fluff (fabric, rubber, glass, etc.). The iron and steel are magnetically separated from the other materials and recycled.

The iron and steel is then shipped to end markets or steel mills where it is recycled to produce new steel, most of it going to the construction industry.

By weight, the typical passenger car consists of about 65% steel and iron. The steel used in car bodies is made with about 25% recycled steel.

Environmental benefits

Recycling steel saves energy and natural resources. The steel industry annually saves the equivalent energy to power about 18 million households for a year. Recycling one ton of steel conserves 2500 pounds of iron ore, 1400 pounds of coal and 120 pounds of limestone.

ELV = End-of-Life Vehicle
ASR = Automotive Shredder Residue
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 Spangenberg works at the next separation station.
RAINING PLASTIC – Chemist Joe Pomykala checks the flow of polyolefin coming from a tank that separates the recycled auto plastic concentrate into its constituent parts.

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.
Recent Trends in Automobile Recycling: Economic, Social, and Energy Issues

![Image of recycled plastics in a BMW 3-series](image)

The study estimated that during the coming decade the quantity of energy used in the manufacture of automobiles will increase (because of the increased use of plastics and aluminum); the energy consumed during the life of the automobile will decrease (in response to new technologies and lightweight materials); and, somewhat surprisingly, the energy savings from the recycling of automobiles will increase (primarily because of the increased recycling of aluminum).

The adoption of new recycling technologies and approaches (e.g., thermoplastic recycling and incineration of automobile shredder residue) will have little impact on energy savings at the recycle step.
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.

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.
APPENDIX: Some useful numbers when considering automobiles

1 U.S. gallon = 3.78 L

# mpg (miles per gallon) = \( \frac{235.55}{\# \text{ L per 100 km}} \)

- 14 L / 100 km = 16.8 mpg
- 10 L / 100 km = 23.6 mpg
- 7 L / 100 km = 33.7 mpg
- 3.9 L / 100 km = 60.4 mpg

The average fuel efficiency of cars in the U.S. is 22.4 mpg (10.5 L / 100 km)

1 L of gasoline delivers 31 MJ and generates 2 kg of CO₂

1 barrel of oil weighs 106 kg and contains 42 U.S. gallons = 0.159 m³ = 6.12 GJ

1 hp = 0.74570 kW

A typical automobile driving at 55 mph (90 km/h) consumes 28 kW of power