16.682: Technology in Transportation - Pset #1 Solutions

Issued: Tuesday, February 1st, 2011

Due: Thursday, February 10th, 2011

Topics Covered: Energy in Transportation

Note: Make sure to list all assumptions based on your background search.

16.682 PS 1 Ans.

Question 1: Human energy

a) Step 1: Vehicle efficiency:

- 2010 Toyota Camry 4-cyl: 22mpg city (Source: toyoota.com).

Driving 2 miles uses $\dfrac{2\text{mi}}{22\text{mpg}} = 0.091$ gal of gas

- Petroleum refining efficiency: $T_p =$ 0.830

→ search "well-to-wheel" efficiency (source: ODE 10CFR part 474)

$$0.091gal \cdot \frac{3.78L}{1gal} \cdot \frac{34.8\text{MJ}}{L} \cdot \frac{1}{0.830} = 14.4\text{MJ}$$

Step 2: Human efficiency: (Answers will vary)

- Calories burned by walking 2 miles (source: nutristrategy.com)

155-lb person walking @ 3.0mph burns 232 Cal/hr

→ 2miles = $\frac{2}{3} \cdot 232 = 154.6$ Cal.

154.6 Cal = 0.644 MJ used

2 slices of standard wonderbread @ 80 cal each weigh 60g (30g each).

0.06 kg ·15MJ/kg = 0.9 MJ.

Total energy used in walking = 0.9 + 0.644 MJ = 1.544 MJ

→ If you only eat bread, your total energy usage would be $\boxed{10.7\%}$ of driving.

Note that this doesn't account for the energy used in making the oil thousands of years ago, which would push this number even lower.

b) Assume 3,000 mi. are covered:

i) 2010 4-cyl Camry gets 33 mpg hwy

→ will use $\dfrac{3,000}{33} = 91\text{gal} = 343.6\text{L}$

gasoline ≈ 35 MJ/L (source: wikipedia's sources)

total: 12,027 MJ → 4MJ/mi → 1MJ/mi · passenger

ii) Typing "amtrak efficiency" into Google yields 2,398 BTU/passenger-mile at the first search result link.

2,398 BTU → 2.53 MJ/mi·passenger

iii) Boeing 747 efficiency → looking at the boeing spec sheet:

Range: 13,450 km = 8,357 mi

Max. Pass: 524

Max. Fuel: 57,285 gal = 216,840L

jet fuel: Also 35.1 MJ/L

$$\frac{216,850\text{L} \cdot 35.1\text{MJ/L}}{8,357\text{mi} \cdot 524\text{pass}} = 1.73 \text{ MJ/(mi} \cdot \text{ pass)}$$

Question 2: Solar Power:

1) - Assuming total electricity usage is about what if was in 2009 (3,741 billion kWh: source.

- Best location for panels is southern Nevada (insolation is $\sim$ 7.0 kWh/m^2/day source: NREL 2004)

- Specs of CS6p-220 -p panel:

$/Watt = 1.69

Area = $1.61m^2$

Output = 220W

Efficiency (Test @ 1,000 W/m^2 irradiance)=$\frac{220\text{W}}{1,610\text{W}} = 13.7\%$

At an isolation of 7.0 kWh/m^2/day, this panel would provide 0.956 kWh/day $\rightarrow$ 349 kWh/yr.

$$\frac{3.741 \cdot 10^{12} \text{ kWh/yr}}{349\text{kWh/yr}} = \boxed{1.07 \cdot 10^{10} \text{ solar panels required}}$$

At $371.8/panel, this is $\boxed{\$ \ 3.98 \cdot 10^{12}}$

Total coverage area:

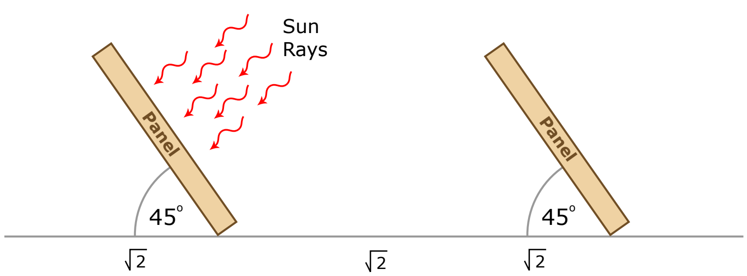

Image by MIT OpenCourseWare.

$\rightarrow$ to allow for rotation of the panels and solar ray tracking, gaps must be left in between the panels.

$\rightarrow$ Total packing efficiency $\sim$ 50%.

$1.07 \cdot 10^{10}$ panels $\cdot 1.61 \ m^2 \cdot \frac{1}{0.5} = 11.724 \text{E}10 \ m^2$

$= 3,328$sq.mi = All of puerto rical / about 3 rhode islands.

2) Avg. cost of electricity across all sectors: 9.94 cents/kWh

$\Rightarrow$ U.S. spends \$ $3.72 \cdot 10^{11}$/yr on electricity, vast majority of which comes from coal.

$$\frac{3.98 \cdot 10^{12}}{3.72 \cdot 10^{11}} = \boxed{10.7 \text{ years}}$$

3) In perfect sun, these panels output 220W each → 68 of them. 109 m^2 of panel.

A standard tractor trailer is $2.44\text{m} \times 16.15\text{m} = 39.4\ \text{m}^2 \Rightarrow$ almost 3 tractor trailer worth of solar panels (with no drag)

Question 3: Biofuels:

Ethanol yield per acre: 3,800 Liters/hectare (10,000 m^2) → per year.

(source: Wiki's sources)

US Gasoline Consumption: 378 million gal/day (source: DOE, google)

→ 5.5×10^{11} liters/yr

$$\frac{5.5 \times 10^{11}\text{liters/yr}}{3,800\text{liters/yr}} = 1.44 \times 10^{8}\text{hectares}$$

= 1.44 E8 m^2

Accounting for the energy difference in ethanol vs. gasoline (ethanol has about 60% of the energy content of gasoline), final answer comes to 2.36 E8 m^2 (91,000 sq miles, about the size of Oregon).

4. Electric Vehicles and Gas-Electric Hybrids:

Tesla Motors has claimed that the Roadster electric sports car is 2x more efficient than a Toyota Prius. Is this true? Is it always true? Under what conditions?

One very good resource to get started:

Tesla Roadster Efficiency

Quoted Rage (web): 245 miles

Quoted Battery Pack Size: 54 kWh

Estimated Average Efficiency: ~220 Wh/mile

Toyota Prius Efficiency

Quoted Mileage: 51/48/50 MPG (city/highway/combined)

Energy Content, US Gasoline: 33,705 Wh/gal (wikipedia)

Calculated Efficiency: (33,705 Wh/gal) / (50 miles/gal) = **674 Wh/mile**

So, on paper, the Tesla Roadster appears to be approximately 3x as efficient as the Toyota Prius using their quoted ranges. I found the following chart of theoretical Roadster efficiency on the Tesla engineering blog: source

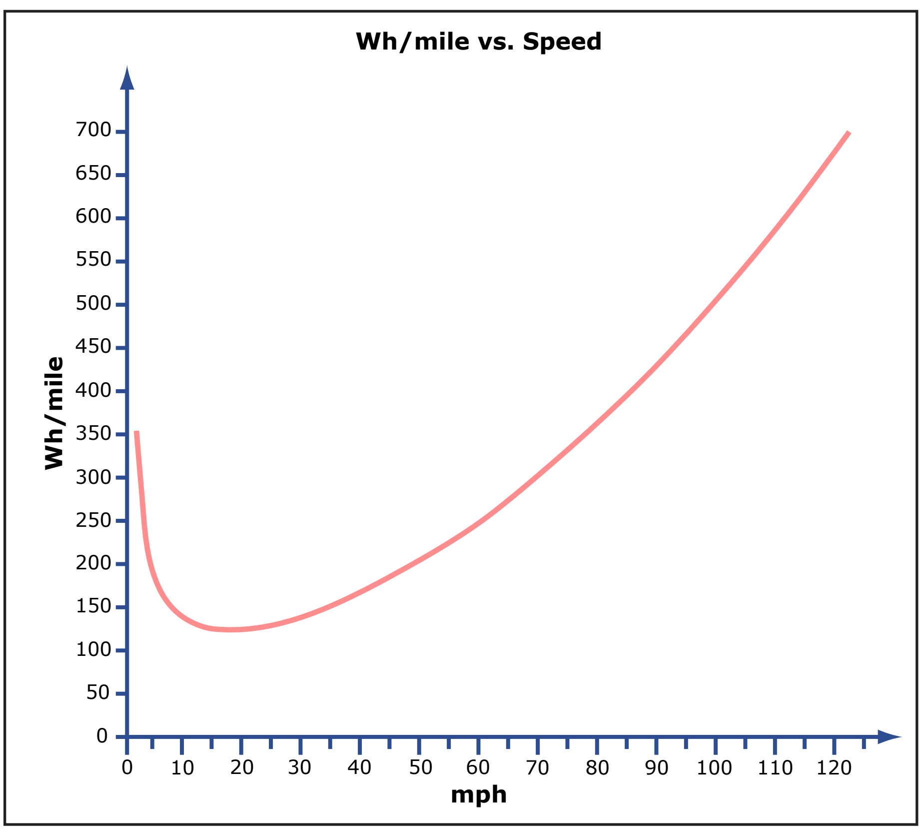

Image by MIT OpenCourseWare.

The following plot is from a Prius Forum where a user logged OBD-II (on board diagnostics) fuel data from a prius and plotted the resulting efficiencies vs vehicle speed. Source 1 and Source 2

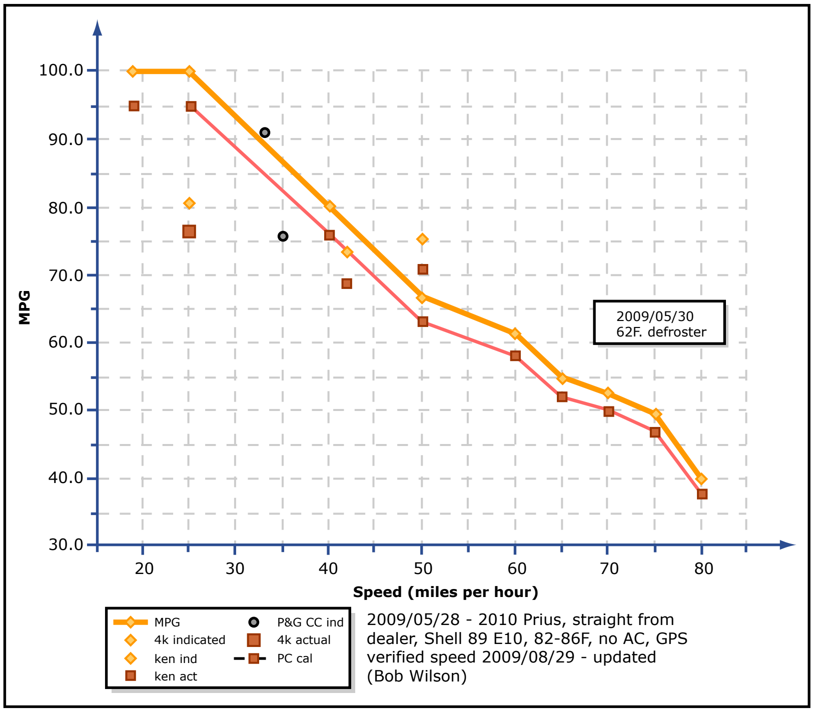

Image by MIT OpenCourseWare.

First of all, notice that the top speed of the Roadster is **125 mph** (on the chart at least) as compared to **80 mph** for the Prius. Also, while the Roadster efficiency is provided in terms of watt-hours/mile, the prius efficiency is provided in terms of miles/gallon, so the 2 curves are correct to have inversely related trends.

Here is an important conversion factor for our purposes:

(1 kWh/mile) / (33.705 kWh/gal) = **.0300 gal/mile**

- or -

1 mile/kWh = **33.71 miles/gallon**

So, let's create a table relating the efficiencies of the Roadster and Prius at various speeds:

Average Speed	**Roadster**	**Prius**
20 mph	140 Wh/mi -> **240.8 mpg**	**100 mpg**

40 mph	175 Wh/mi -> **192.6 mpg**	**77.5 mpg**
60 mph	250 Wh/mi -> **134.8 mpg**	**60 mpg**
80 mph	360 Wh/mi -> **93.6 mpg**	**37.5 mpg**
100 mph	500 Wh/mi -> **67.4 mpg**	**x**
120 mph	650 Wh/mi -> **51.9 mpg**	**x**

Clearly, the relative efficiencies of the Roadster and the Prius depend highly upon the way the vehicles are being use. A Roadster owner who drives his vehicle at 120 mph at all times, even through school zones, just to look cool, will get only half the efficiency as a super eco-conscious Prius owner driving 20 mph at all times.

It is important to note that these are efficiencies predicted for **constant driving speeds**. The actual fuel consumption will be impacted significantly by accelerations and decelerations of the vehicles. For instance, if two identical vehicles drive over a stretch of road with the same average velocities, but one has a fluctuating speed while the other holds his or her speed perfectly constant, the one that accelerates and decelerates more will consume more fuel. So, an extremely aggressive Roadster driver (it is a sport car after all), may consume close to the same energy as a conservative eco-conscious Prius driver who never touches the brakes.

5. Greenhouse Gas Emissions:

Compare the greenhouse gas emissions of operating an electric vehicle vs. an internal combustion engine (ICE) vehicle.

a) Assume grid electricity is generated using the following mix: 7% hydroelectric, 20% nuclear, 24% natural gas, 45% coal, 4% renewable. Reference resource

Generation Method	Greenhouse Gas Emissions (Tons CO_2 / kWh)
Hydroelectric	~0
Nuclear	~0
Natural Gas	(117,000 lbs/billion BTU) = 0.40 lbs CO2/kWh
Coal	(208,000 lbs/billion BTU) = 0.71 lbs CO2/kWh
Other Renewables	0

Source

Assumptions:
Electric Vehicle Efficiency = 350 Wh/mile
Electric Grid Efficiency = 0.9

Electricity Emissions = 0.24 * (0.4 lbs CO2/kWh) + 0.45 * (.71 lbs CO2/kWh) = **0.42 lbs CO2/kWh**
EV Emissions = (0.42 lbs CO2/kWh * 0.350 kWh/mile) / (0.9 grid efficiency) = **0.16 lbs CO2/mile**
Average Fuel Economy, Internal Combustion Engine Vehicle = 27.5 mpg -> CAFE standards for 2011
CO_2 Content, Gasoline = 20 lbs / gallon gasoline

ICE Emissions = (20 lbs CO2/ gallon) / (27.5 mpg) = **0.73 lbs CO2 / mile**

b) Now, assume electricity is generated from only 2 sources: zero emissions renewables (or could be nuclear) and coal. Is there a breakeven point between the proportion of renewables to coal at which ICE vehicles become "cleaner" than electric vehicles in terms of carbon dioxide emissions? Where in the country might this make a difference?

Assume that the average electric vehicle consumes 350 Wh/mile and come up with reasonable values for all other numbers.

EV Emissions = (0.71 lbs CO_2/kWh)*(% coal) / (0.9 grid efficiency) =.73 lbs CO_2 / mile = ICE Emissions

Coal = 92.5% of Grid Electricity
Renewables = 7.5% of Grid Electricity

Of course, these numbers depend on our assumptions for ICE vehicle mileage, EV Efficiency, and other factors. However, it is apparent that a grid has to be very dependent on carbon-intensive coal in order for EV's to come close to breaking even with ICE carbon dioxide emission levels.

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