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Biking or driving a car: how much fossil-fuel energy do we use? Where does the energy go, in the end? How long can we keep going, whether by foot or by fuel?

Contents

Fossil energy use is significant in a car, but also in getting food into our bodies so that we can bike

It seems intuitive that less energy is used transporting ourselves by walking or on a bike than by car, given the need to move such a large mass of metal in a car. Let's compare the energy use…but we have to use a common basis for comparing the energy use. We don't want to use food calories for our human-powered movement but fossil fuel energy for our vehicular transportation.

In fact, there is a relation between food energy and fossil-fuel energy. David Pimentel and his research group did a thorough study of the use of fossil-fuel energy (FFE) in producing food **[1]**. Some FFE inputs are obvious, such as fuel used by tractors and other mechanized farm machinery for plowing, application of herbicides and pesticides, and harvesting, as well as fuel used by food-processing plants and, ultimately delivery trucks, both long-haul and local (note that the average potato sold in the US is transported 500 miles!). Perhaps less-obvious FFE inputs are in the production of nitrogenous fertilizers and pesticides. Worldwide, the far-dominant forms of nitrogenous fertilizers are made as or from ammonia, NH_3, and, in turn, the chemical synthesis of ammonia is quite energy-intensive **[2]**. Overall, ammonia synthesis consumes 3% of total human energy supplies worldwide, comparable to all the airlines in the world **[3]** . (Ammonia, on average among all production plants, embodies the use of about 36 MJ per kg, nearly the same as gasoline; see www.fertilizer.org, though this site quotes only 1.2% as the fraction of world energy used by ammonia production.)

To continue, the Pimentel group calculated that producing a calorie in food delivered for consumption requires, on average, 2.6 calories of fossil fuel energy; it depends on your diet, of course, with meat-intensive diets representing much higher values (e.g., it takes about 7 times the mass of feed as mass in meat to raise the meat animals **[4]**; the energy ratio is perhaps half this, because beef is more energy-dense per mass). We have to inflate that by about 3/2, because Americans, at least, waste on average 1/3 of purchased food. Let's also get to metabolic energy, which is, on average, about 85% of the energy ingested in food, because digestion only captures that 85% of the energy in food (http://en.wikipedia.org/wiki/Food_energy), with the rest being expended in the digestive process itself. OK, so we now take 2.6 units of fossil energy per unit of energy in delivered food and convert that to(3/2)*2.6 = 3.9 units per unit of energy in consumed food and then convert that to (1/0.85)*3.9 = 4.6 units per unit of energy in useful metabolic energy.

Estimating fossil energy that supported us in riding a bike, per mile

So, let's get to one of us on a fairly good bike. We might comfortably reach a steady 10 mph. In my survey of diverse sources, popular and scientific, I found considerable discordances about the metabolic effort in biking at this or other speeds. The most reliable data are from the European Journal of Applied Physiology, Vol 67, pp. 144-149 (1993). The data are for trained cyclists on aerodynamic bikes, so we'll probably have to double the results for average humans on average bikes. The authors directly measured metabolic costs via oxygen consumption rates above baseline (resting metabolism), as a function of bike speed. They covered higher speeds from about 10 mph upward (4.7 to 11.1 m/s) and found that the metabolic cost of biking was close to a constant plus a factor varying as the square of the speed (from wind resistance, mostly). The cost was $(30 + 0.6\ v^2)$ J per m traveled, with speed in meters per second. Now, 10 mph is about 4.5 m s^{-1}, so that the cost of biking was about 42 J m^{-1} for these cyclists on fine bikes. Let's estimate 84 J m^{-1} for our average people on average bikes. I'll move to the usually execrable English units to convert this to cost per mile, using 1610 m per mile, to get 135 kJ per mile. At 10 mph, the metabolic rate per mile is then estimated at 1350 kJ/h, or 323 kcal/h. This is the right order of magnitude; basal metabolism is about 50 kcal/h and reasonably vigorous exercise "burns" an additional 300 kcal h^{-1}.

OK, our metabolic energy cost is to be inflated by the factor of 4.6 computed two paragraphs earlier to estimate the fossil-fuel calories used all the way up the line to get that energy out of us. We now have 4.6*135 kJ mi^{-1}, or 620 kJ mi^{-1}.

Comparison: fossil energy use in going by car, also per mile

Now to the car. Let's assume a modern car, with a city/highway average fuel economy of 25 mpg, the US estimated fleet average for ***new*** cars, light trucks, and SUVs used for personal transportation **[5]**. (I have serious doubts that people achieve this level, with their less-than-optimal driving habits, and the all-vehicle average is significantly lower when one considers the older cars that dominate in numbers). In 1 mile of travel with one person aboard (typical! US average light-vehicle occupancy is only 1.67! **[6]**), the vehicle uses 0.04 gal of gasoline. Since a gal is 3.78 liters, this is 0.151 L. The energy density of gasoline averages about 35 MJ/L **[7]** , so that the in-vehicle consumption of energy is about 5.3 MJ. This is about 8.5 times the FFE consumed in biking the same distance. I am actually surprised that the factor is as small as 8.5. You might take this to mean that it's about equally efficient for 8 or 9 of us to take a trip in a single vehicle as it is for those same 8 or 9 of us to ride bikes. Of course, our other impacts on society differ; bikers make CO_2 metabolically, in that 1:8.5 ratio to vehicular travel, but few volatile organic compounds that cause smog formation (we do emit volatiles from our skin, alas); the 8 or 9 bikers are better than the 8 or 9 people in a car, on that count. You can find out various other facts, for sure.

Note: for both the food system's use of fossil energy and the car's use of same, I'm using the fuels after refining. Energy use in refining makes both consumption rates scale up by the factor of (raw fuel energy in)/(refined fuel energy out). This is perhaps 1/0.9 for gasoline, based on incurred costs [**8**], but this favorable figure discounts the need to push significant fractions of crude oil into lower-value products such as residual oil, asphalt, and waxes.

Walking rather than biking

Interesting fact: walking takes about 2 or 3 times as much energy per unit distance traveled as does biking under the stated conditions [**9**], so that it's not that great compared to driving in a car. Running is, surprisingly, more efficient as lower energy per distance; our metabolic rate doesn't increase as fast as our speed does.

Biking, but not eating the average American diet

Another fact: food raised in the mode called organic (a term that doesn't sit well with someone who has done research in both chemistry and biology, but let it be a useful discriminant) uses far less fossil-fuel energy to get to us, and vegetarian food also uses less. The figure of merit (distance traveled per unit fossil fuel involved) can be very high for biking by people on these diets.

Some further considerations

Efficiency of mechanical work, humans vs. engines powered by fossil fuels

Muscles have a peak energy efficiency, from metabolic energy to mechanical energy output, of about 28%, depending on muscle type and loading conditions [**10**]. It's reduced under common conditions when the biomechanical linkage is not effective (e.g., in moving a light ball by kicking, most of our mechanical energy output just goes into moving and then stopping our legs.) The internal combustion engine varies widely in the efficiency with which it delivers final motive power, such as to the road for a car. It's common peak value with modern engines and transmissions might be 25%, with an average of perhaps less than 20% [**11**]. Electric vehicles use electric motors that may have 85% to 90% energy efficiency, but the electric power is mostly generated by burning fossil fuels at a power plant with 40% to 45% energy efficiency, so that their efficiency from fuel to road-delivered energy might max out at 0.90*0.45 = 40.5%. It's usually lower; at dead start, an electric motor has zero efficiency (power is consumed but speed is zero).

Efficiency of human motion

OK, our muscles convert a modest fraction of metabolic energy into the work of overcoming various energy dissipating processes (rolling and aerodynamic resistances and gear losses when biking, e.g.), and in vehicles similar processes (rolling and aerodynamic resistances) require input of energy from an engine. Can we give a figure for the efficiency of transport in any mode, as the theoretical minimum divided by the actual energy expended? We compute such efficiencies for moving heat with refrigerators or heat pumps. For transport on level ground, however, the theoretical minimum energy use is zero! An object, including us, moved across level ground, has the same gravitational potential energy at the beginning and the end; there's no gain or loss. When we're stationary, there's no kinetic energy at the beginning or the end. So, what do we value in transport, since the energy used is all degraded to heat in the end? Is it time? We pay for speed. Is it social contact? Keep thinking.

Where did the energy of muscular effort in walking, running, or biking go?

We admit to ourselves that we didn't store any of this energy as changes in mechanical energy in us or in the environment, nor did we store it in other forms such as (bio)chemical energy. It all got degraded to forms of energy that we may justly call lower forms. In thermodynamics, we distinguish free energy [**12**] from total energy, with free energy being the part that can do work, such as mechanical work or electrical work. There's no absolute scale for free energy – rather, we can compute the difference in free energy between any two states, which might be described by many things – e.g., for a homogeneous gas by its temperature, pressure, and volume. For heat engines, such as the internal combustion engine (ICE), heat is moved from a high temperature condition (the newly combusted fuel-air charge) to a low temperature condition (the exhaust gas, esp. after its dilution in air). The maximal fraction of total energy that is free energy in such a system is ($1-T_{hot}/T_{cold}$); here, all temperatures must be used as absolute temperatures, T above absolute zero. In an ICE that theoretically might operate at a high-temperature side of, say, 1000°C = 1273 K (Kelvin) absolute and 25°C = 298 K, the fraction of free energy is 1-298/1273 or 77%. Clearly, ICEs don't come close, with engine friction, heat loss to cylinder walls, incomplete expansion to outdoor temperature, etc.

Back to where the energy went: let's take walking or running. We worked against air resistance, moving the air, in which viscous forces in eddies eventually turned the energy of motion into heat, making the air slightly warmer. We also compressed or displaced some of the surface, which returned to a static state just a little warmer. We moved muscles and tendons internally against mechanical resistances. We lost energy to various other modes (which you may try enumerating). In the end, the energy all became heat and nothing got much warmer. Even if we could capture the heat in whatever we warmed slightly, we would not capture much free energy. If we warmed parts of our body from, say, 30°C = 303 K in an extremity (arm or leg, cooler than our core 37°C), to 31°C = 302 K, the fraction of free energy in that heat is 1-301/302 = 0.0033 = 0.33%. Let's face it, we eventually lost all the free energy.

Losing all the free energy is the ultimate fate of the energy we expend, or virtually anything else on Earth

We're not the only ones on Earth using energy for transport, or for many other purposes. Plants grow, using solar energy (even the saprophytic organisms such as fungi that grow on dead matter, because that dead matter came from living plants or from living plants through animals that ate them). Solar energy also heated the Earth's surface differentially, creating winds, but winds don't keep accumulating (except, perhaps, in Wyoming!); their energy gets dissipated to heat. All that solar input eventually gets converted to simple heat. The heat then leaves the Earth as thermal radiation, out to space. This can lead to a discussion of the Earth's energy balance, the greenhouse effect, and more, which is best done in a separate discussion. Of course, there are energy sources on Earth that aren't solar, with a prime example being the energy coming from the Earth's interior, where it was deposited at the time of the Earth's formation as 1) the gravitational energy from accretion from dispersed particles in the solar nebula (a loss) converted to heat and 2) the potential decay energy of radionuclides that were created by the supernova that predated the solar system; the main power now comes from the decay of uranium 238 (8 terawatts), thorium 232 (8 TW), and potassium 40 (4 TW) **[13].** It's noteworthy that all potassium is radioactive, even that nutritive potassium in your food and then in your body. It's very, very weakly radioactive, however, with a half-life of about 1.25 billion years. Not much is decaying in your body.

Capital and maintenance energy

The energy use we've been calculating, whether for biking, driving, walking,
+home heating, or whatever, is what we may term the operational energy. That excludes the energy use over the lifetime of the "prime mover." We should add what we may call capital energy, that needed to make the powered device, and maintenance energy, that needed for repairs. Then we may distribute these costs over the lifetime of the mover. For the average US vehicle, estimates of the energy input to manufacture it ranged from 13 to 52 gigajoules, with refined estimates developed later [**14**]. Distributing the upper estimate over a lifetime driving distance of 150,000 mi, this adds a cost of transport of 350 kJ per mile. Let's compare this to the energy used in operating the vehicle, which is 5.3 MJ per mile, as computed earlier...or about 16 times more. Looking at it another way, building a car takes no more than about 1/16th as much energy as is used in operating it over its lifetime. For making a bicycle, a rough estimate is that the energy use incurs the emission of about 530 pounds of CO_2 [**15**]. We can back-calculate that, assuming some of the energy came from coal (coke, in steelmaking) and some from oil or natural gas (to make electric power). We'll assume that the mix of sources makes for an energy yield of 30 MJ per kg of fuel, halfway between coal and oil, and the carbon content of fuel is also in the middle, at about 95%, or 0.95 kg of C per kg of fuel. Then, 1 kg of fuel combusted releases 8.1 lb of CO_2 (CO_2 has a molecular mass of 44, C has an atomic mass of 12, so that there's 44/12 times as much mass of CO_2 as carbon consumed, and 1 kg is 2.2 lb). Then, 530 lb of CO_2 should come from combusting 530/8.1 = 66 kg of fuel. That much fuel had an energy content of nearly 2.0 GJ - about 1/26th as much as the car/truck with about 100 times the mass; auto manufacturers are more efficient. How long does a bike last, in distance traveled, for the average person? That is a hard number to come by. We'll make a major guess and say that a more dedicated rider who wants to save energy rides about 5 miles per day on average on a bike that lasts 15 years, about as long as the average car. That makes a total distance of 5 x 365 x 15 miles or just over 27,000 miles (about 18% as far as the average car might go in its lifetime). Distributing the capital energy over 27,000 miles gives an amortized capital energy cost of 74 kJ per mile. Compare this to the estimate of 620 kJ per mile in operational energy – it's only about 12%. Capital energy is more important in some other energy conversion devices. For a big electric power plant, I found an Australian estimate that the capital energy is about ¼ of the total electric energy delivered over its lifetime, a lot bigger fraction [**16**]. Maintenance energy costs are smaller yet than capital energy in all these devices. For living green plants, however, maintenance costs dominate [**17**]. Plant cells, like all living cells, are constantly pumping ions to counteract leaks and constantly renewing proteins.

Fossil fuel (and other large energy sources) have really amplified the power that humans control today (though maybe not for long!)

Muscle power vs. fuels in human history

For most of human history (and prehistory), muscle power was our only significant source of motive power – human and domestic animal muscle. This discounts the odd water or wind mill. Rich people had power at their command primarily via the slave system, not something that could ever multiply power for the world. The spectacular increase in available power came with the discovery that fossil fuels could be extracted and used in heat engines, such as James Watt's steam engine – notably inefficient (3%) [**18**] but more powerful than a team of men. While some people say that science per se gave us power, it was the fossil fuels that made power abundant. Jeremy Grantham [**19**] pointed out that, while striking advances in science came around the time of Isaac Newton, there was no real use of fossil fuels and people still were hungry and ill-served for growing food, transporting themselves and their goods, and keeping warm or cool. In the last 250 years, humans have now burned through a major portion of fossil fuels, spending out the largesse of the Earth, the captured solar energy of dead organisms metamorphosed into coal, oil, and gas. There is much more to be extracted and burned, but there are two great barriers to using the reserves of fossil fuels. One is the rapidly growing cost of extraction. Oil has been above $85 per barrel and is not coming down in the long term, because the reserves are more diffusely placed, locked into resistant or deep strata, or both. The other barrier is the usage penalty of environmental change. Smog and black carbon pollution is one impact of fossil-fuel combustion, though remediable by emission controls, even if the massive new fossil-fuel power plants coming online in China have very poor controls. Greenhouse gas impact and attendant climate change is effectively irremediable over the typical lifetime of major civilizations, measured in hundreds of years or, at the most, a few thousand. Carbon dioxide has a mixed set of residence times in the air, with the shortest decay time (for transport into oceans, uptake by net plant growth, etc.) of over 150 years.

Getting over the limitations of using up fossil fuels

The "outs" for us, as long-term energy sources, are of two kinds: long-term depletable and renewable. In the long-term depletable category we may put nuclear fission (though we can also count it as a relic of past times of nucleosynthesis, a sort of fossil), nuclear fusion, and geothermal. Fission fuel reserves are very large, particularly if we count thorium that's 3 or 4 times more abundant than uranium, all fissionable (vs. uranium, mostly U-238 that has to be either rejected or bred to plutonium), and usable with great efficiency in liquid fluoride molten salt reactors [**20**]. Nuclear fusion has been called the energy source of the future, or, more wryly, the energy source of the future and it always will be. It has proven extremely difficult to generate net power from fusion of hydrogen isotopes and commercialization, at best, is far off.

Geothermal energy I count as depletable because we are not going to use the steady-state flux of only 0.065 watts per square meter [**21**], averaged over the Earth's land surface. That's a flux that is almost 1/4000th the size of solar energy. Over the land area of the US, for example, that flux amounts to 600 gigawatts (about 9.8 million km^2 = $9.8\text{x}10^{12}$ m^2, multiplied by 0.06 W m^{-2}, or about $6\text{x}10^{11}$ W). Compare this to the US primary energy use, quoted as about 3 TW **[22]**, 5 times larger. The only practical geothermal energy is from special locations with water flux (geysers, in effect), natural or aided. And there, we really *mine* the thermal energy, never to be replaced for thousands or tens of thousands of year, beyond a human time scale. A recent scientific publication **[23]** reiterates the estimate that tapping only 2% of the heat in the depths from 3.5 to 10 km could supply 2,000 times the annual use rate of the US. Let's check that. Assume, of course, that geothermal wells that deep could be drilled and maintained practically (not a given!). Suppose that there's a temperature differential of 200°C to be exploited in the hot, relatively deep rock. Take the density of rock at 4,000 kg per cubic meter, and note that there is a volume of 6.4 x 10^{16} m^3, computed as US land area, 9.8 x 10^{12} m^2 times 6.5 km = 6.5 x10^3 m (depth). The corresponding mass of rock is this figure multiplied by 4,000 kg m^{-3}, or about 2.56 x 10^{20} kg. With a heat capacity of roughly 1 J per gram per degree C or 10^3 J kg^{-1} K^{-1}, the heat content of this rock is 2.56 x 10^{23} J. Two percent of this is 5.12 x 10^{21} J. The annual US energy use, at 3 TW over 3.1 x 10^7 s in a year, is then 9.3 x 10^{19} J. The figure I just got for geothermal extraction is a bit over 500 times larger – not 2,000 times, but a large number. One has to do some discounting: the free energy content is lower than the gross energy content, or enthalpy. One can't generate electricity, for one, at the 40% energy efficiency typical for fossil-fuel combustion – one might expect about 10% to 15% at the very best.

We'll be using a lot more land for energy production

I may point out that we have used up much of the energy sources that have small footprints, as land use per unit of energy extracted. Coal strip mines are big scars on the land, but with coal seams 20 meters deep that take land out of use for 40 years, the average yield of final electric power is about 140 watts per square meter (about 14% of peak sunlight or about 60% of average sunlight at the surface). Solar PV farms yield about 30 watts per square meter (average sunlight energy density of about 234 W m^{-2}, 15% practical energy efficiency, some downtime). Oil and gas extraction have extremely variable 'footprints,' yielding very low to very large power densities per unit of land committed. While there is an understandable natural human reaction to deploying solar panels over vast areas of desert (or any other land), there's no alternative for solar power to being land-hungry. Energy crops are worse, having gross energy capture in plant matter of about 1% and great use of water (even interception of rainfall has impacts on water availability, because aquifer recharge can be notably affected). Wind power is also dilute or land-intensive, estimated as about 1 W m^{-2} [**24**, referenced in **25**]; very high kites might have high power densities without tying up land use, though they are not near practicality yet. In short, we have to get used to having much of our energy supply coming from large areas of land. "Not in my back yard" as a philosophy is going to change.

References other than those detailed within the text:

These are primarily Web references, which are easier to find and which often contain primary references

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[18] http://library.thinkquest.org/20331/history/timeline1600.html quotes a work production of 20 million foot-pounds from a bushel of coal. We can convert ft-lbs to joules by multiplying by 0.305 m/ft, then by 0.45 kg/lb, and finally by 9.8 m s^{-2}, the acceleration of gravity, obtaining 27 MJ. A bushel of coal weighs 80 lb or 36 kg and has an energy content of about 24 MJ/kg, so that the total energy in the coal (plus the air) is 864 MJ. The efficiency is 27/864 = 3.1%

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